



(11)

EP 3 314 217 B1

(12)

EUROPEAN PATENT SPECIFICATION

(45) Date of publication and mention of the grant of the patent:
01.02.2023 Bulletin 2023/05

(51) International Patent Classification (IPC):
B01L 3/00 ^(2006.01) **G01F 1/704** ^(2006.01)
G01F 1/708 ^(2022.01)

(21) Application number: **16817372.2**

(52) Cooperative Patent Classification (CPC):
B01L 3/502715; G01F 1/7046; G01F 1/708;
B01L 2300/0645; B01L 2300/0663; B01L 2300/0816

(22) Date of filing: **28.06.2016**

(86) International application number:
PCT/IL2016/050687

(87) International publication number:
WO 2017/002109 (05.01.2017 Gazette 2017/01)

(54) SYSTEM AND METHOD FOR MEASURING FLOW

SYSTEM UND VERFAHREN ZUR MESSUNG DES DURCHFLUSSES

SYSTÈME ET PROCÉDÉ DE MESURE D'ÉCOULEMENT

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB
GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO
PL PT RO RS SE SI SK SM TR

US-A1- 2011 198 225 US-A1- 2012 322 076
US-B2- 7 225 683 US-B2- 7 225 683

(30) Priority: **28.06.2015 IL 23969115**

(43) Date of publication of application:
02.05.2018 Bulletin 2018/18

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Description

FIELD AND BACKGROUND OF THE INVENTION

[0001] The present invention relates to fluidic systems and, more particularly, but not exclusively, to a system and method for measuring flow.

[0002] Much industrial and academic effort is presently directed at the development of integrated micro devices or systems combining electrical, mechanical and/or optical/electrooptical components, commonly known as Micro Electro Mechanical Systems (MEMS). MEMS are fabricated using integrated circuit batch processing techniques and can range in size from micrometers to millimeters. These systems can sense, control and actuate on the micro scale, and function individually or in arrays to generate effects on the macro scale. MEMS include numerous applications, such as airbag accelerometers, ink-jet heads, radio frequency micro-switches for wireless communications, micro-gyroscopes, digital micro-mirror displays, pico-satellites and the like.

[0003] Whenever mechanics can replace electronics, it provides superior functionality and is not subject to undesirable electronic noise. For example, the classical electronic components of fiber-optic networks are now being replaced with optical MEMS switches that enable the creation of arrays of miniature high capacity switches which can play a critical role in the development of large-scale optical switches in fiber-optic networks.

[0004] MEMS may consist of mechanical microstructures, microsensors, microactuators and electronics integrated in the same environment (e.g., on a silicon chip). The microfabrication technology enables fabrication of large arrays of devices, which individually perform simple tasks but in combination can accomplish complicated functions. For example, MEMS for guidance, navigation, motion control and high resolution flow visualization can provide experimental evidence about smallscale phenomena and thus verify fundamental principles in the microcosm.

[0005] One type of MEMS is a microfluidic device. Microfluidic devices include components such as channels, reservoirs, mixers, pumps, valves, chambers, cavities, reaction chambers, heaters, fluidic interconnects, diffusers, nozzles, and other microfluidic components. These microfluidic components typically have dimensions between a few micrometers and a few hundreds of micrometers. The small dimensions of the components minimize the physical size, the power consumption, the response time and the waste of the entire system. Such systems may provide wearable miniature devices located either outside or inside the human body.

[0006] Applications for microfluidic devices include genetic, chemical, biochemical, pharmaceutical, biomedical, chromatography, integrated circuit cooling, ink-jet printing, medical, radiological and environmental applications. The medical applications include diagnostic and patient management such as implanted drug dispensing

systems. The environmental applications include detecting hazardous materials or conditions such as air or water pollutants, chemical agents, biological organisms or radiological conditions. The genetic and biochemical applications include testing and/or analysis of DNA, and other macro or smaller molecules, or reactions between such molecules in microfluidic devices, in an approach known as "lab-on-chip."

[0007] Microfluidic devices presently occupy an increasingly significant position in chemical and biochemical sensing, molecular separations, drug delivery and other forefront technologies. In a manner similar to that for microelectronics, microfluidic technologies enable the fabrication of highly integrated devices applicable to high throughput, low volume, automatable chemical and biochemical analyses and syntheses. Common fluids used in microfluidic devices include whole blood samples, bacterial cell suspensions, protein or antibody or nucleic acid solutions and various buffers.

[0008] Known in the art are thermal flow sensors that include a heating element immersed within fluidic channel. Upon application of forced fluid flow in the channel, temperature changes relative to the base state of the heating element are measured. The flow alters the temperature distribution through heat convection, and the measurement allows determining the flow rate in the channel.

[0009] United States Patent 7,225,683 discloses a device for measuring the flow rate of a fluid in a flow channel. The device includes means for creating localized compositional variations in the fluid along the flow axis, means for subsequently detecting the compositional variation at a point downstream from its point of creation, and means for measuring flight time. The device is capable of measuring flow rates from less than about 1 nL/min to greater than about 10 μ L/min at pressures as great as 1.379×10^7 pa (2,000 psi).

SUMMARY OF THE INVENTION

[0010] The present invention provides a microfluidic system according to claim 1, and a method of sensing flow of fluid in a microchannel according to claim 13.

[0011] Unless otherwise defined, all technical and/or scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which the invention pertains. Exemplary methods and/or materials which can be used in the practice or testing of invention are described below. In case of conflict, the patent specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and are not intended to be necessarily limiting.

[0012] Implementation of the method and/or system of embodiments of the invention can involve performing or completing selected tasks manually, automatically, or a combination thereof. Moreover, according to actual instrumentation and equipment of embodiments of the

method and/or system of the invention, several selected tasks could be implemented by hardware, by software or by firmware or by a combination thereof using an operating system.

[0013] For example, hardware for performing selected tasks according to embodiments of the invention could be implemented as a chip or a circuit. As software, selected tasks according to embodiments of the invention could be implemented as a plurality of software instructions being executed by a computer using any suitable operating system. In an exemplary embodiment of the invention, one or more tasks according to exemplary embodiments of method and/or system as described herein are performed by a data processor, such as a computing platform for executing a plurality of instructions. Optionally, the data processor includes a volatile memory for storing instructions and/or data and/or a non-volatile storage, for example, a magnetic hard-disk and/or removable media, for storing instructions and/or data. Optionally, a network connection is provided as well. A display and/or a user input device such as a keyboard or mouse are optionally provided as well.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Some embodiments of the invention are herein described, by way of example only, with reference to the accompanying drawings. With specific reference now to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of embodiments of the invention. In this regard, the description taken with the drawings makes apparent to those skilled in the art how embodiments of the invention may be practiced.

[0015] In the drawings:

FIGs. 1A and 1B show representative example of a concentration polarization (CP) effect demonstrated according to some embodiments of the present invention;

FIG. 2 is a schematic illustration of a microfluidic system, according to some embodiments of the present invention;

FIGs. 3A-C are useful to understand the invention and schematically illustrate a representative mode of operation of a microfluidic system in which a separate pair of electrodes is used for sensing;

FIGs. 4A-C schematically illustrate an additional representative mode of operation of a microfluidic system according to some embodiments of the present invention; and

FIG. 5 is a schematic illustration of a microfluidic system, in embodiments of the invention in which the system includes a pump and a controller.

FIGs. 6A and 6B show images of a prototype sensor system used in experiments performed to demonstrate the present invention;

FIGs. 7A-D show computer simulation results useful

to understand the present invention;

FIG. 8A is a series of images showing snapshots of a main channel of the prototype sensor system at different times during flow of 1 mM KCl at average speed of 66.4 $\mu\text{m/s}$, as measured in experiments performed to demonstrate the present invention;

FIG. 8B includes graphs that are useful to understand the invention and which show normalized impedance and normalized intensity of a signal, as a function of the time, as measured in experiments performed to demonstrate the present invention;

FIGs. 9A and 9B are graphs that are useful to understand the invention and which show correlations between the flow speed of 1 mM KCl (in $\mu\text{m/s}$) and two measured parameters: the time to saturation of the impedance (FIG. 9A), and the change in electrical impedance during saturation (FIG. 9B);

FIGs. 10A-D are graphs that are useful to understand the invention and which show results of measurements taken across a membrane of the prototype sensor system, during flow of 1 mM KCl, as obtained in experiments performed to demonstrate the present invention; and

FIGs. 11A-C are graphs that are useful to understand the invention and which show results of measurements taken across a membrane of the prototype sensor system, during flow of insulin, as obtained in experiments performed to demonstrate the present invention.

DESCRIPTION OF SPECIFIC EMBODIMENTS OF THE INVENTION

[0016] The present invention relates to fluidic systems and, more particularly, but not exclusively, to a system and method for measuring flow.

[0017] Before explaining at least one embodiment of the invention in detail, it is to be understood that the invention is not necessarily limited in its application to the details of construction and the arrangement of the components and/or methods set forth in the following description and/or illustrated in the drawings and/or the Examples. The invention is capable of other embodiments or of being practiced or carried out in various ways.

[0018] The present invention induces a concentration polarization (CP) effect for measuring a flow parameter. In this effect local ionic concentration gradients are generated at an interface of fluid and an ion permselective medium upon application of voltage or current across the permselective medium. More specifically an enriched ionic concentration is formed at one side of the permselective medium and a depleted ionic concentration is formed at its opposite side, when both sides interface a fluid. When a pair of electrodes is in contact with the fluid (e.g., submerged) a change of the ion concentration can be electrochemically generated, for example, by a process of electrolysis of a solvent or species dissolved therein. Specifically, local composition variations can be

formed by electrochemical oxidation or reduction of a redox couple at each electrode of the pair, thereby producing a region of increased or decreased conductivity that can be used to determine fluid flow rate.

[0019] A representative example of the CP effect is shown in FIGs. 1A and 1B. FIG. 1A is an image of a nanochannel **10** having negative surface charges and being flanked by two microchannels **12** arranged co-linearly. The microchannels are filled with a solution containing a KCl electrolyte and Rhodamine 6G fluorescent dye. An electric field is applied across the nanochannel. The direction of the electric field is shown by arrow **14**. A microscopic image of nanochannel **10** and microchannels **12** is shown in FIG. 1B. As shown in FIG. 1A, ionic concentration polarization is generated at both sides of nanochannel **10** wherein a depletion of ions is formed at a region marked by arrow **18** and an enrichment of ions is marked by arrow **16**.

[0020] FIG. 2 is a schematic illustration of a microfluidic system **20**, according to some embodiments of the present invention.

[0021] The term "microfluidic system" as used herein refers to a system having one or more fluid microchannels.

[0022] The term "microchannel" as used herein refers to a fluid channel having crosssectional dimensions the smallest of which being less than 1 mm, more preferably less than 500 μm , more preferably less than 400 μm , more preferably less than 300 μm , more preferably less than 200 μm , e.g., about 100 μm or about 10 μm .

[0023] Thus, system **20** comprises one or more fluidic microchannels, such as, but not limited to, microchannels **12**. Microchannel **12** can be a linear microchannel, in which case microchannels **12** extends along a generally (e.g., within deviation of 10% or less) straight line, or a nonlinear microchannel, in which case at least part of microchannels **12** extends along a curved line. Microchannel **12** can also be formed of a plurality of interconnected segments. These embodiments include a configuration in which all the segments are linear, or configuration in which all the segments are nonlinear, or a configuration in at least one of the segments is linear and at least one of the segments is nonlinear.

[0024] The length of microchannel **12** can vary, depending on the application for which system **20** is employed. As a representative non-limiting example, the overall length of microchannel **20** is from about 0.1 cm to about 20 cm.

[0025] System **20** also comprises a sensor system generally shown at **22**.

[0026] Sensor system **22** detects at least one flow parameter characterizing the flow in microchannel **12** by exploiting the aforementioned CP effect. Sensor system **22** comprises one or more ion permselective medium **11** having a first side **24** and a second side **26**.

[0027] Ion permselective medium **11** can be any medium made, at least in part from a permselective material, and can have any structure, including, without limitation,

a nanostructure, a nanoporous membrane and an electrode. The permselective medium **11** can, in some embodiments, be embodied as a permselective nanochannel, such as, but not limited to, nanochannel **10**.

[0028] Ion permselective medium **11** is positioned in microchannel **12** to allow contact of sides **24** and **26** with the fluid in microchannel **12**. This creates an interface between the fluid in microchannel **12** and medium **11**, thereby allowing sensor system **22** to utilize the CP effect.

[0029] System **20** further comprises an arrangement of electrodes **28** arranged to generate an electric field across permselective medium **11**. This can be done by connecting electrodes **28** to a power source **36**, which may effect an electrical potential difference across permselective medium **11**. Via the CP effect, ionic concentration gradients are formed in microchannel **12**, near sides **24** and **26** of permselective medium **11**. FIG. 2 illustrates two electrodes **28a** and **28b** positioned outside microchannel **12**. These electrodes do not necessarily be positioned in the vicinity of the permselective medium **11**, but can also be applied further away (e.g., via electrodes immersed within the reservoirs of the inlets/outlets of the microchannels). However, this need not necessarily be the case, since, for some applications, it may be

desired to position electrodes **28** inside microchannel **12**.

[0030] In various exemplary embodiments of the invention system **20** comprises an ion concentration sensing system **38** configured to provide sensing signals indicative of ion concentration patterns (for example, shape, size) effected by the flow of fluid in the microchannel. These patterns typically constitute ionic concentration gradients. Optionally and preferably, system **20** or **22** comprises a controller **37** that controls power source **36** to ensure that the duration of the electric field generated by electrodes **28** is longer than, e.g., at least twice, the time required for the sensing signals provided by system **38** to exhibit saturation.

[0031] The time required for the sensing signals to exhibit saturation is referred to herein as "time-to-saturate" and denoted τ . The time-to-saturate τ can be defined as a difference $t_1 - t_0$ between two instants of time t_1 and t_0 , where t_0 is an onset time of the electric field, and t_1 is an instant of time at which the time-derivative of the signal, in absolute value, reaches about 20% or 10% or 5% of its value at time t_0 .

[0032] As used herein, "saturation" of a signal means a situation in which the magnitude of the signal does not vary by more than X% over a period of time that is at least the time-to-saturate τ , where X is about 20 or about 10 or about 5.

[0033] Typically, but not necessarily, a situation in which the magnitude of the signal does not vary by more than 20% or more than 10% or more than 5% or over a period of 1 second or 2 seconds.

[0034] Ion concentration sensing system **38** can be of any type that is sensitive to ionic concentration and that can generate signals indicative of ion concentration patterns. Representative examples of such systems include,

without limitation a spectroscopic system (e.g., atomic absorption spectroscopy, UV-visible spectroscopy etc.), an optical sensing system, an electric sensing system and a magnetic sensing system.

[0035] In some embodiments of the present invention ion concentration sensing system **38** has a sensing element **38a**, which can be embodied, for example, as a pair of electrodes, which provides sensing signals indicative of a local ion concentration pattern. In some embodiments of the present invention sensing element **38a** is proximal to permselective medium **11**, but embodiments in which the sensing element is placed downstream or upstream medium **11** are also contemplated. In some embodiments of the present invention system **22** detects the flow parameter(s) by analyzing a sensing signal received from a single sensing element (e.g., sensing element **38a**) of ion concentration sensing system **38**.

[0036] According to the invention, the electric field and the sensing signals are generated by the same set of electrodes, e.g., electrodes **28**. Electrodes **28** are optionally and preferably within channel **12**. System **22** can be devoid of passive electrodes such as electrodes **38**. Thus, for example, the system can include a pair of electrodes positioned at opposite sides of the permselective medium, in contact with the fluid, wherein these electrodes are used both for generating an electric field and for sensing the ion concentration pattern across the permselective medium.

[0037] In some embodiments of the present invention, sensing system **38** is embodied as an arrangement of electrode pairs (e.g., a first pair of electrodes **38a**, and a second pair of electrodes **38b**) that are employed as one or more sensing pairs wherein electrical current, electrical impedance, electrical resistance, electrical conductance or the like, that is sensed by these pairs of electrodes is indicative of conductivity patterns near or at these electrodes. Since conductivity correlates with ion concentration, each of the pairs **38a**, and **38b** can serve as sensing elements in ion concentration sensing system **38**.

[0038] While some embodiments are described with a particular emphasis to an ion concentration sensing system which is an electric sensing system, it is to be understood that more detailed reference to an electric sensing system is not to be interpreted as limiting the scope of the invention in any way.

[0039] System **20** comprises a signal processor **30** configured for analyzing the signals provided by system **38** and for determining at least one flow parameter characterizing the flow in microchannel **12**. For clarity of presentation, processor **30** is shown to be connected only to electrode pair **38b**, but in a preferred embodiment the processor **30** communicates with all the sensing elements of system **38** and/or electrodes **28**. For example, when electrodes **28** are used both for generating an electric field and for sensing the ion concentration pattern across the permselective medium, processor **30** communicates with electrodes **28**, and system **20** can, but not

necessarily, be devoid of electrodes **38**.

[0040] Processor **30** can include an analog circuit for performing the analysis or it can include an analog-to-digital circuit form converting the signal to digital signals and a digital processing circuit for performing at least a portion of the analysis in a digital manner.

[0041] The parameter determined by processor **30** can be a numerical parameter such as, but not limited to, flow rate, a change in flow rate (e.g., the time-derivative of the flow rate and/or a gradient of flow rate), and a flow direction. The parameter is optionally and preferably extracted after a calibration process from raw local measurements of electrical parameter such as, but not limited to, an electrical current, an electrical impedance, an electrical resistance and/or an electrical conductance. The parameter determined by processor **30** can also be a local numerical parameter, such as, but not limited to, velocity vector field, change in the velocity field (e.g., the time-derivative of the velocity field and/or a gradient of velocity field) and the direction of the velocity field vector. The advantage of determining the direction of the flow is that it allows sensor system **22** to measure the flow parameter both when the fluid flow in one direction in microchannel **12**, and when the fluid flow in the opposite direction in microchannel **12**.

[0042] When the sensing elements of system **38** comprise electrodes (e.g., electrode pairs **38a** and **38b**) the sensing elements can be positioned in proximity to sides **24** and **26** of medium **11**. Alternatively or additionally, one or more of the sensing elements is positioned farther from the respective end. When the sensing elements are in proximity to sides **24** and **26** of medium **11**, processor **30** optionally and preferably measures changes in the conductivity pattern at sides **24** and **26**.

[0043] Processor **30** can determine the flow pattern in more than one way. In some embodiments of the present invention processor **30** extracts from the sensing signals generated by one or more the sensing elements an electrical parameter (e.g., an electrical current, an electrical impedance, an electrical resistance and/or an electrical conductance), and correlates the extracted electrical parameter(s) to the flow parameter, optionally and preferably by direct correlation. The electrical parameter can be extracted separately from signals provided by different sensing elements, so that signals received from a single sensing element can be used by processor **30** to determine the flow parameter. When several sensing elements are used, processor **30** can determine the flow parameter based on signals received from any of these sensing elements. Preferably, processor **30** monitors the signals received from one or more of the sensing elements and determines whether or not these signals exhibit saturation, wherein the electrical parameter(s) are extracted during the saturation phase of the signals.

[0044] Processor **30** can also receive from controller **37** a clock signal indicative of the onset time of the electric field across medium **11**, and use this clock signal to determine the elapsed time from the onset of the electric

field to the onset of saturation. In these embodiments, processor **30** can optionally and preferably correlate this elapsed time to the flow parameter.

[0045] Processor **30** can also determine the flow parameter by means of a time-of-flight (TOF) measurements. These embodiments are useful when there is one or more sensing elements that is located proximal to medium **11**, and one or more additional sensing elements located farther from medium **11**, downstream with respect to medium **11**. Processor **30** can measure the time interval that passes when the concentration pattern moves from medium **11** to the sensing element (referred to herein as the TOF of the concentration pattern). The TOF can be defined as the elapsed time between receipts of signals from the sensing element proximal to medium **11** and the sensing element farther and downstream from medium **11**.

[0046] System **22** can employ two or more of the above techniques for determining the flow parameter, and output the result of each of these techniques, e.g., to a display device **31**. Alternatively or additionally, processor **30** can output only a selected result, based on a predetermined criterion, such as, but not limited to, reproducibility and definiteness (non-ambiguity).

[0047] Thus, sensor system **22** optionally and preferably mimics a MEMS based thermal flow-meter sensor since it allows measuring the flow (a) at the permselective medium; (b) in proximity to the permselective medium; and/or (c) farther from the permselective medium, downstream therefrom.

[0048] Configuring processor **30** for determining any of the above parameters can be by calibration. For example, known flow rates can be transmitted through microchannel **12** and the signals from system **38** and/or electrodes **28** can be recorded and their pattern can be stored in a recording medium. In operation, processor **30** can compare the received signals with the stored signals and determine the flow rate based on the comparison. Similarly, known changes in flow rates can be transmitted through microchannel **12** and the signals from electrodes **28** can be recorded and their pattern can be stored in a recording medium. In operation, processor **30** can compare the received signals with the stored signals and determine the change of flow rate based on the comparison. Similarly, known flow directions can be transmitted through microchannel **12** and the signals from system **38** can be recorded and their pattern can be stored in a recording medium. In operation, processor **30** can compare the received signals with the stored signals and determine the direction of flow based on the comparison.

[0049] In any of the above calibration procedures, rather than storing the recorded patterns themselves, a calibration curve or lookup table can be stored on a computer readable medium. Such calibration curve or lookup table can include correlations found during the calibration process between the measured parameter (e.g., electrical parameter, time to reach saturation, time-of-flight) and the flow parameter, such that in operation, processor

30 extracts the respective parameter from the signals and correlates it to the flow parameter using the calibration curve or lookup table. Representative examples of calibration curves suitable for the present embodiments are shown in the Examples section that follows (see, for example, FIGs. 7D, 9A, 9B, 10C, 10D, 11B and 11C).

[0050] Typically, the recording and comparison and/or correlation are done digitally, in which case processor **30** is a digital signal processor. However, recording and comparison of analog signals and the use of analog processor is also contemplated.

[0051] System **20** can be used to convey, handle or analyze many types of fluids in microchannel **12**. Representative examples including, without limitation, water, a biological fluid (for example, body fluid, e.g., blood, plasma, urine, saliva, vaginal secretions, feces, interstitial fluid, wound excrement), a bacterial cell suspension, a protein medium, an antibody medium, a nucleic acid medium, ink, and fluid media commonly used in standard medical applications such as phosphate buffered saline or other medicinal liquids (e.g., insulin, growth hormone, hemostatic agent solution). The fluid may include one or more types of objects therein, such as, but not limited to, a mixture of cell types. The fluid can also be of any type, including any chemical analytes, reagents, compounds etc.

[0052] Typically, sensor system **22** of system **20** is useful for measuring relative low flow rates (e.g., flow rate of less than 500 microliter per minute, or less than 100 microliter per minute, or less than 50 microliter per minute, or less than 25 microliter per minute, or less than 10 microliter per minute, or less than 5 microliter per minute, or less than 1 microliter per minute, or less than 0.1 microliter per minute, or less than 0.01 microliter per minute).

[0053] A representative mode of operation of the microfluidic system in which a separate pair of electrodes is used for sensing is illustrated in FIGs. 3A-C. In this example, microchannel **12** is a branched fluidic microchannel, and medium **11** is embodied as a cation permselective membrane (e.g., Nafion) and is positioned to connect between two branches **32** and **34** of microchannel **12**. FIG. 3A illustrates a static state in which no flow is forced into microchannel **12**. Upon application of a voltage drop between electrodes **28a** and **28b** a depletion and enrichment ionic concentration layers are formed at the anodic and cathodic sides of the membrane **11**, respectively.

[0054] FIG. 3B illustrates a state in which flow is forced into microchannel **12**. The pattern of depletion and enrichment ionic concentration layers is changed due to the flow in branches **32** and **34**, respectively. This change is sensed, for example, as the difference between the ion concentration (or proxy thereof) measured by sensing element **38a** and the ion concentration (or proxy thereof) measured by sensing element **38b**, both within the depletion ionic concentration deformed layer. This difference is correlated to the magnitude of the flow within

microchannel **12**. In the no-flow case

[0055] (FIG. 3A) this difference vanishes. This change can additionally or alternatively be sensed as the difference between the ion concentration (or proxy thereof) measured by sensing element **38c** and the ion concentration (or proxy thereof) measured by sensing element **38d**, both within the enrichment ionic concentration deformed layer. This change can additionally or alternatively be sensed also using a single sensing element, which can be the sensing element proximal to the as further detailed hereinabove.

[0056] FIG. 3C illustrates a configuration in which additional sensing elements **38e**, **38f** are positioned downstream the flow relative to membrane **11**. These sensing elements can be used to measure the elapsed time for the depletion ionic concentration layer to propagate from element **38a** to element **38e** (interchangeably referred to as the time-of-flight of the depletion ionic concentration layer) and/or the enrichment ionic concentration layer to propagate from element **38c** to element **38f** (interchangeably referred to as the time-of-flight of the enrichment ionic concentration layer).

[0057] Another example of a possible mode of operation of the microfluidic system of the present embodiments is illustrated in FIGs. 4A-C. In this example, microchannel **12** is a non-branched fluidic microchannel, and medium **11** is embodied as a cation permselective membrane (e.g., Nafion) and is positioned to connect between two separate microchannels **33** and **35** at the opposite sides of the main microchannel **12**. The two side microchannels **33** and **35** do not necessarily contain the same fluid as in microchannel **12**. In some embodiments of the present invention they contain a stagnant electrolyte that allows the introduction of electrodes **28b** for application of an electric field through the permselective medium.

[0058] In the specific example shown in FIGs. 4A-C electric field, optionally and preferably a symmetric electric field, with the line of symmetry along microchannel **12**, is applied resulting in symmetric enrichment concentration layers within microchannels **33** and **35** and a symmetric depletion concentration layer within the main microchannel **12**. In this example of a cation permselective membrane, electrodes **28b** are cathodes preferably having the same negative potential, and electrodes **28a** are anodes preferably having the same positive potential.

[0059] However, the setup is not limited to the application of such a symmetric electric field and the electrodes **28b** within the top side microchannel **35** can have a different potential from the electrodes **28b** at the bottom side microchannel **33**. For example, when the former have a higher potential than that of the latter, and electrodes **28a** are merely floating, then both enrichment and depletion ionic concentration layers develop within the microchannel **12**.

[0060] FIG. 4A illustrates a static state in which no flow is forced into microchannel **12**. Upon application of a voltage drop between electrodes **28a** and **28b** depletion and

enrichment ionic concentration layers are formed at the anodic and cathodic sides of the membrane **11**, respectively.

[0061] FIG. 4B illustrates a state in which flow is forced into microchannel **12**. The pattern of depletion ionic concentration layer is changed due to the flow in the main microchannel **12** while the pattern of the enrichment ionic concentration layers is barely changed as the side microchannels do not sustain net flow. This change can be sensed by one of the sensing elements (e.g., sensing element **38a**), for example, by extracting from the signal one or more electrical parameters or the time for saturation, and executing a correlation procedure to the flow parameter as further detailed hereinabove. This change can alternatively or additionally be sensed as the difference between the ion concentration (or proxy thereof) measured by sensing element **38a** and the ion concentration (or proxy thereof) measured by sensing element **38b**. This difference is correlated to the intensity of the flow within microchannel **12**. In the no-flow case (FIG. 4A) this difference vanishes. This change can additionally or alternatively be sensed as the difference between the ion concentration (or proxy thereof) measured by sensing element **38c** and the ion concentration (or proxy thereof) measured by sensing element **38d**.

[0062] FIG. 4C illustrates an embodiment in which additional sensing elements **38e**, **38f** are positioned downstream the flow relative to membrane **11**. These sensing elements can be used to measure the time-of-flight of the depletion ionic concentration layer from element **38a** to element **38e**, and/or from element **38c** to element **38f**.

[0063] In various exemplary embodiments of medium **11** is made, at least in part, of a permselective material. The use of permselective material is advantageous because it enhances the CP effect at sides **24** and **26** of medium **11**.

[0064] The term "permselective material," as used herein, refers to an ion permeable material having the property that the ion transport number (also called the transference number, and is the fraction of the total current carried by a given ion) through the material is higher for ionic species having a certain charge sign than for ionic species having the opposite charge sign.

[0065] In some embodiments of the present invention permselective material has the property that the transport number through the material is higher for ion of one species than for ions of another species.

[0066] For example, in a permselective material such as a cation exchange membrane, cations pass through the material more easily (i.e., while experiencing less resistive force) than anions. In a permselective material such as an anion exchange membrane, anions pass through the material more easily (i.e., while experiencing less resistive force) than cations.

[0067] A permselective material is different from a porous structure that does not discriminate among differently charged ionic species as the species pass through the porous structure.

[0068] In some embodiments of the present invention the permselective material comprises a cation exchange material which is non-permeable to anions, and in some embodiments of the present invention the permselective material comprises an anion exchange material, which is non-permeable to cations.

[0069] A variety of permselective materials may be employed for medium 11. Representative examples including, without limitation, the sulfonic acid substituted perfluorocarbon polymers of the type described in U.S. Patent No. 4,036,714; the primary amine substituted polymers described in U.S. Pat. No. 4,085,071; the polyamine substituted polymers of the type described in U.S. Pat. No. 4,030,988; and the carboxylic acid substituted polymers described in U.S. Pat. No. 4,065,366.

[0070] Examples of sulfonic acid substituted type materials include perfluorosulfonate cation exchange materials such as those membranes marketed commercially under the trademark NAFION®, manufactured and sold by the E.I. duPont de Nemours, Wilmington, DE. Typical membranes include the NAFION® 200 series, NAFION® 204, 214, 255, 295, the NAFION® 300 series, NAFION® 313, 315, 316, 324, 336, 337, 355, 376, 390, 391, and the NAFION® 400 series including NAFION® 427 membrane, mixtures thereof and the like. Also contemplated is the use of an amniotic membrane extract (AMX) as a permselective medium.

[0071] Medium 11 can be a nanochannel with at least one of its dimensions of the same order of magnitude as size of the electric double layer (EDL) so as to induce the overlap of EDLs from opposite channel walls. Techniques suitable for making such nanochannels, include, without limitation, photolithography, nanofabrication techniques such as focused-ion-beam (FIB), E-beam, nano-imprint lithography and the like.

[0072] Other ion permselective materials can be made of electrodes that support reaction with only one ionic species, such that effectively, it can be considered as permselective only for this ionic species that pass current through the reactions and leads to CP.

[0073] When permselective medium 11 is embodied as an electrode in direct contact with the fluid, it can comprise an adhesion layer (e.g. chromium, titanium, tantalum) and a conductive layer deposited thereon (e.g. gold, platinum).

[0074] A variety of materials and processes can be used to form microchannel 12. In some cases, the various materials selected lend themselves to fabrication techniques. For example, microchannel 12 can be formed from solid materials, in which the microchannels can be formed via molding, micromachining, film deposition processes such as spin coating and chemical vapor deposition, laser fabrication, photolithographic techniques, etching methods including wet chemical or plasma processes, and the like. Also contemplated are three-dimensional freeform fabrication techniques, such as three-dimensional jet printing, wherein patterns of printed material allow directional fluid transport.

[0075] At least a portion of microchannel 12 can be formed of a polymer, for example, an elastomeric polymer such as polydimethylsiloxane (PDMS), polytetrafluoroethylene (PTFE) or the like. Technologies for precise and efficient formation of microfluidic systems from such materials are known.

[0076] Microchannel 12 can be conveniently formed of a hardenable fluid, facilitating formation via molding (e.g., replica molding, injection molding, cast molding, etc.). The hardenable liquid can be essentially any liquid that can be induced to solidify, or that spontaneously solidifies, into a solid capable of containing and/or transporting fluids contemplated for use in and with a microfluidic system. In one embodiment, the hardenable liquid comprises a polymeric liquid or a liquid polymeric precursor. Suitable polymeric liquids can include, for example, thermoplastic polymers, thermoset polymers, or mixture of such polymers heated above their melting point. As another example, a suitable polymeric liquid may include a solution of one or more polymers in a suitable solvent, which solution forms a solid polymeric material upon removal of the solvent, for example, by evaporation. Such polymeric materials, which can be solidified from, for example, a melt state or by solvent evaporation, are well known to those of ordinary skill in the art. A variety of polymeric materials, many of which are elastomeric, are suitable. A non-limiting list of examples of such polymers includes polymers of the general classes of silicone polymers, epoxy polymers, and acrylate polymers. Epoxy polymers are characterized by the presence of a threemembered cyclic ether group commonly referred to as an epoxy group, 1,2-epoxide, or oxirane. For example, diglycidyl ethers of bisphenol A can be used, in addition to compounds based on aromatic amine, triazine, and cycloaliphatic backbones. Another example includes the well-known Novolac polymers. Non-limiting examples of silicone elastomers suitable for use according to the invention include those formed from precursors including the chlorosilanes such as methylchlorosilanes, ethylchlorosilanes, phenylchlorosilanes, etc.

[0077] In some cases silicone polymers are used. A representative example includes the silicone elastomer PDMS, which is commercially available, e.g., from Dow Chemical Co., Midland, Mich. Silicone polymers including PDMS have several beneficial properties simplifying formation of microchannel 12. For instance, such materials are inexpensive, readily available, and can be solidified from a liquid polymeric precursor via curing with heat. PDMSs are typically curable by exposure of the liquid polymeric precursor to temperatures of about 70 °C for exposure times of about an hour. Elastomeric polymer materials are also advantageous for their inertness to critical components of an analysis or synthesis to be carried out. Elastomeric polymer materials can also be coated with suitable materials as known in the art.

[0078] Other types of materials for microchannel 12 are also contemplated. Suitable materials are generally selected based upon their compatibility with the manu-

facturing process (injection molding, dry etching, embossing, bonding, soft lithography, stereolithography and three-dimensional jet printing, etc.) and the conditions present in the particular operation to be performed by the microfluidic system. Such conditions can include extremes of pH, pressure within the microchannels, temperature, ionic concentration, and the like.

[0079] Electrodes **28** can be made of any electrically conductive material, such as, but not limited to, a metal (e.g., gold, platinum, silver or silver chloride). Alternatively, electrodes **28** can be made of a semiconductor material, such as, but not limited to, a p-doped or n-doped semiconductor material (e.g., silicon electrode doped with boron or silicon electrode is doped with phosphorous). In embodiments in which the sensing elements of system **38** include electrodes, these electrodes can be made of any of the aforementioned electrically conductive or semiconductor materials.

[0080] Generally, the microfluidic system of the invention can be used in many applications, preferably applications that require relatively low flow rate as indicated above. Representative example of suitable applications include without limitation, genetic applications, chemical applications, biochemical applications, pharmaceutical applications, biomedical applications, chromatography applications, integrated circuit cooling, ink-jet printing, medical applications, radiological applications and environmental applications.

[0081] A representative application which can employ the microfluidic system of the present embodiments is illustrated in FIG. 5. In this representative application, microfluidic system **20** comprises a pump **42** for generating flow in microchannel **12**, and a controller **44** configured for controlling pump **42** responsively to the flow parameter determined by sensor system **22**, thereby forming a closed loop control between pump **42** and sensor system **22**. A representative utilization of this application is the medical field, for example, for the administration of a compound to a subject. For example, the system can be used as an insulin pump for providing a controlled rate of insulin delivery to a diabetic subject who would normally need multiple daily injections to regulate the blood glucose level. Existing pumps may not be as accurate as required by a particular treatment protocol, and the closed loop control of the present embodiments improves the accuracy of the delivery rate.

[0082] The system of the present embodiments is useful also for other medical applications, particularly but not necessarily for diagnostic and patient management. For environmental applications the microfluidic system of the present embodiments is suitable for detecting hazardous materials or conditions such as air or water pollutants, chemical agents, biological organisms or radiological conditions. For genetic and biochemical applications the microfluidic system of the present embodiments is suitable for testing and/or analysis of DNA, and other macro or smaller molecules, or reactions between such molecules in an approach known as "lab-on-chip."

[0083] The microfluidic system of the present embodiments can be used to obtain a variety of measurements including, without limitation, molecular diffusion coefficients, fluid viscosity, pH, chemical binding coefficients and enzyme reaction kinetics. Other uses for the microfluidic system of the present embodiments include, without limitation, immunoassays, flow cytometry, sample injection of proteins for analysis via mass spectrometry, sample injection of air or water samples for analysis via flamespectrometry, polymerase chain reaction (PCR) amplification, cell manipulation, cell separation, cell patterning and chemical gradient formation. Many of these applications have utility for basic research and clinical diagnostics.

[0084] The microfluidic system of the present embodiments can be integrated in microchips, such as DNA chips, protein chips and total analysis systems. For example, the microfluidic system of the present embodiments can be integrated in a DNA chip which includes a substrate for which probes with known identity are used to determine complementary binding, thus allowing massive parallel gene expression and gene discovery studies. The use of the microfluidic system of the present embodiments with such microchip can facilitate the production of small and high density spots on the substrate. Since only a small amount of solution is needed to make one chip, the cost of chip production is substantially reduced. In addition, the microfluidic system of the present embodiments can create spots in consistent quantities and with uniform shape and size, so as to allow highly accurate comparisons between spots.

[0085] The microfluidic system of the present embodiments can also be used as a chromatograph for performing liquid chromatography.

[0086] The microfluidic system of the present embodiments can also be used as a microfluidic printing device, in which inks are formed by moving precursors through microchannels.

[0087] The microfluidic system of the present embodiments can also be used as a microfluidic mixer, in which one or more fluids are moved through a mixer inserted in a microchannel.

[0088] The microfluidic system of the present embodiments can also be used as an optical device, in which a bubble or slug of fluid immiscible in a second fluid is moved through the second fluid to a spot of optical activity on the substrate.

[0089] The term "consisting essentially of" means that the composition, method or structure may include additional ingredients, steps and/or parts, but only if the additional ingredients, steps and/or parts do not materially alter the basic and novel characteristics of the claimed composition, method or structure.

[0090] As used herein, the singular form "a", "an" and "the" include plural references unless the context clearly dictates otherwise. For example, the term "a compound" or "at least one compound" may include a plurality of compounds, including mixtures thereof.

[0091] Throughout this application, various embodiments of this invention may be presented in a range format. It should be understood that the description in range format is merely for convenience and brevity and should not be construed as an inflexible limitation on the scope of the invention. Accordingly, the description of a range should be considered to have specifically disclosed all the possible subranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed subranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6 etc., as well as individual numbers within that range, for example, 1, 2, 3, 4, 5, and 6. This applies regardless of the breadth of the range.

[0092] Whenever a numerical range is indicated herein, it is meant to include any cited numeral (fractional or integral) within the indicated range. The phrases "ranging/ranges between" a first indicate number and a second indicate number and "ranging/ranges from" a first indicate number "to" a second indicate number are used herein interchangeably and are meant to include the first and second indicated numbers and all the fractional and integral numerals therebetween.

[0093] It is appreciated that certain features of the invention, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment.

[0094] Certain features described in the context of various embodiments are not to be considered essential features of those embodiments, unless the embodiment is inoperative without those elements.

[0095] Various embodiments and aspects of the present invention as delineated hereinabove and as claimed in the claims section below find experimental support in the following examples.

EXAMPLES

[0096] Reference is now made to the following examples, which together with the above descriptions illustrate some embodiments of the invention in a non-limiting fashion.

[0097] FIGs. 6A and 6B show images of a prototype sensor system used in experiments performed according to some embodiments of the present invention, where FIG. 6B is a magnified view of a dotted portion shown in FIG. 6A. The prototype system included two side channels, a main channel, and a NAFION® membrane connecting each of the side channels to the main channel. In the experiments, a positive electrical potential was applied at the ends of the main channel and a negative electrical potential was applied at the ends of the NAFION® membrane. A series of pairs of sensing electrodes was deployed across the main channel, at both sides of the membrane.

[0098] Two types of fluids were used in the experiments: a 1 mM KCl (conductivity of 100 μ S/cm) and In-

sulin (conductivity of 2.1 mS/cm).

[0099] FIGs. 7A-D show computer simulation results of ion concentration during the flow in the main channel, which are useful to understand the invention. FIGs. 7A-C show ion concentration patterns across the main channel at three different flow speeds (about 10⁻⁵ m/s, about 10⁻³ m/s, about 10⁻² m/s, respectively), and FIG. 7D is a graph of the conductivity change $\Delta\sigma$ in S/m as a function of the flow speed U_0 in m/s. The points on the graph marked by (i), (ii) and (iii) correspond, respectively, to FIGs. 7A-C. The simulations demonstrate that the shape and size of the ion concentration pattern is indicative of the flow speed.

[0100] FIG. 8A is a series of images showing snapshots of the main channel at different times ($t = 0, 5, 10, 20, 40, 60, 80, 100$ and 200 seconds) during flow of 1 mM KCl at average speed of 66.4 μ m/s. FIG. 8B shows graphs of the normalized impedance and normalized intensity of the signal, as a function of the time, as measured by a pair of sensing electrodes positioned about 500 μ m downstream the membrane. The location of the sensing pair is marked by a block arrow in FIG. 8A. As shown, the impedance and intensity reached saturation after about 45 second.

[0101] FIGs. 9A and 9B are graphs showing correlations between the flow speed of 1 mM KCl (in μ m/s) and two measured parameters: the time to saturation of the impedance, in seconds (FIG. 9A), and the change in electrical impedance during saturation, in $M\Omega$ (FIG. 9B). As shown, the flow speed correlates well with both the parameters. The measurements were taken by a pair of sensing electrodes positioned about 130 μ m downstream the membrane.

[0102] FIGs. 10A-D are graphs showing results of measurements were taken across the membrane using the same pair of electrodes used for generating the electrical field across the membrane, during flow of 1 mM KCl. FIG. 10A is a graph showing the normalized electrical current as a function of the time in seconds during flow at an average speed of about 62.55 μ m/s.

[0103] As shown, the current reaches saturation about 65 seconds following the onset of the electrical field. FIG. 10B shows the normalized electrical current as a function of the time in seconds for several different flow speeds, and FIGs. 10C and 10D show correlations between the average flow speed in μ m/s and two measured parameters: the electrical current during saturation (FIG. 10C), and the time to saturation of the electrical current, in seconds (FIG. 10D). As shown, the flow speed correlates well with both the parameters.

[0104] FIGs. 11A-C are graphs showing results of measurements were taken across the membrane using the same pair of electrodes used for generating the electrical field across the membrane, during flow of insulin. FIG. 11A shows the normalized electrical current as a function of the time in seconds for several different flow speeds, and FIGs. 11B and 11C show correlations between the average flow speed in μ m/s and two measured

parameters: the electrical current during saturation (FIG. 11B), and the time to saturation of the electrical current, in seconds (FIG. 11C). As shown, the flow speed correlates well with both the parameters. As shown, the flow speed correlates with both the parameters.

[0105] Although the invention has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art; the scope of the invention being defined by the appended claims.

Claims

1. A microfluidic system (20), comprising:

a microchannel (12); and
a sensor system (22) for sensing flow of fluid in said microchannel (12), the sensor system (22) comprising:

a permselective medium (11) positioned to contact the fluid in the microchannel (12);
a power source (36);

an arrangement of electrodes (28), connectable to said power source (36) and arranged to generate an electric field across said permselective medium (11) thereby forming, via the concentration polarization effect, enriched ionic and depleted ionic concentrations in said microchannel (12) near respective opposite ends (24, 26) of said permselective medium (11), and to generate sensing signals indicative of patterns of said ion concentration that are effected by the flow of fluid in said microchannel (12); and

a signal processor (30) for analyzing said sensing signals to determine at least one flow parameter characterizing said flow;

characterized in that:

at least one pair of electrodes (28) that generate said electric field also generate said sensing signals;

wherein said at least one flow parameter is selected from the group consisting of a flow rate, a change in flow rate, a flow direction, a velocity vector field, a change in the velocity field, and a direction of the velocity field vector.

2. The system (20) according to claim 1, wherein said arrangement of electrodes (28) of said sensor system (22) are arranged to sense said patterns at one or two opposite sides of at least one of said ends (24, 26) of said permselective medium (11).

3. The system (20) according to any of claims 1 and 2, wherein said arrangement of electrodes of said sensor system (22) comprises electrodes (38) arranged at to sense said patterns also downstream said flow.

4. The system (20) according to any of claims 1-3, wherein said permselective medium (11) of said sensor system (22) comprises at least one medium selected from the group consisting of: a nanostructure, and a nanoporous membrane.

5. The system (20) according to any of claims 1-4, wherein said permselective material of said sensor system (22) comprises a cation exchange material or an anion exchange material.

6. The system (20) according to any of claims 1-5, wherein said permselective material of said sensor system (22) is polymeric.

7. The system (20) according any of claims 1-6, wherein said at least one flow parameter is selected from the group consisting of flow rate and flow direction.

8. The system (20) according to any of claims 1-7, wherein said signal processor (30) is configured for determining said at least one flow parameter by extracting from said sensing signals at least one electrical parameter, and correlating said at least one electrical parameter to said at least one flow parameter.

9. The system (20) according to any of claims 1-8, wherein said signal processor (30) is configured for determining a time required for said sensing signals to exhibit saturation, and for correlating said time to said at least one flow parameter.

10. The system (20) according to any of claims 1-9, wherein said at least one microchannel (12) is a branched fluidic microchannel, and wherein said permselective medium (11) connects between two branches of said branched microchannel.

11. The system (20) according to any of claims 1-9, wherein said sensor system (22) comprises two secondary microchannels (33, 35) positioned generally parallel to said microchannel (12), such that said permselective medium (11) connects each of said secondary microchannels (33, 35) with said microchannel (12), and wherein said electrodes (28) are arranged to generate said electric field along said secondary microchannels (33, 35).

12. The system (20) according to any of claims 1-11, wherein the microfluidic system (20) comprises a pump (42) for generating said flow, and a controller (37) configured for controlling said pump (42) re-

sponsively to said determined flow parameter.

13. A method of sensing flow of fluid in a microchannel (12), the method comprising:

connecting a plurality of electrodes to a power source to generate electric field across a permselective medium (11) being positioned in the microchannel (12), in contact with the fluid, thereby forming, via the concentration polarization effect, enriched ionic and depleted ionic concentrations in said microchannel (12) near opposite ends (24, 26) of said permselective medium (11);

sensing signals indicative of patterns of said ion concentration that are effected by the flow of fluid in said microchannel (12); and

analyzing said sensing signals to determine at least one flow parameter characterizing said flow;

characterized in that said sensing is by a pair of electrodes (28) that is also used for said generation of said electric field;

wherein said at least one flow parameter is selected from the group consisting of a flow rate, a change in flow rate, a flow direction, a velocity vector field, a change in the velocity field, and a direction of the velocity field vector.

14. The method of claim 13, wherein said generating said electric field is continued for duration longer than a time required for said sensing signals to exhibit saturation.

15. The method according to any of claims 13 and 14, wherein the fluid comprises a solvent and dissolved species, and wherein said electrodes support reaction with only one of said solvent and said dissolved species.

Patentansprüche

1. Mikrofluidisches System (20), umfassend:

einen Mikrokanal (12); und
ein Sensorsystem (22) zum Erfassen eines Fluidstroms im Mikrokanal (12), wobei das Sensorsystem (22) umfasst:

ein permselektives Medium (11), das so positioniert ist, dass es mit dem Fluid im Mikrokanal (12) in Kontakt tritt;

eine Energiequelle (36);

eine Elektrodenanordnung (28), die mit der Energiequelle (36) verbunden werden kann und so angeordnet ist, dass sie ein elektrisches Feld über das permselektive Medium

(11) erzeugt, wodurch mittels des Konzentrationspolarisationseffekts angereicherte und verarmte Ionenkonzentrationen im Mikrokanal (12) in der Nähe jeweiliger gegenüberliegender Enden (24, 26) des permselektiven Mediums (11) gebildet werden, und Erfassungssignale erzeugt, die Muster der Ionenkonzentration anzeigen, die durch den Fluidstrom im Mikrokanal (12) bewirkt werden; und
einen Signalprozessor (30) zum Analysieren der Erfassungssignale, um mindestens einen Strömungsparameter zu ermitteln, der den Strom charakterisiert;

dadurch gekennzeichnet, dass:

mindestens ein Elektrodenpaar (28), das das elektrische Feld erzeugt, auch die Erfassungssignale erzeugt;

wobei der mindestens eine Strömungsparameter aus der Gruppe bestehend aus einer Strömungsgeschwindigkeit, einer Änderung der Strömungsgeschwindigkeit, einer Strömungsrichtung, einem Geschwindigkeitsvektorfeld, einer Änderung des Geschwindigkeitsfelds und einer Richtung des Geschwindigkeitsfeldvektors ausgewählt wird.

2. System (20) nach Anspruch 1, wobei die Elektrodenanordnung (28) des Sensorsystems (22) so angeordnet ist, dass sie die Muster an einer oder zwei gegenüberliegenden Seiten mindestens eines der Enden (24, 26) des permselektiven Mediums (11) erfasst.

3. System (20) nach einem der Ansprüche 1 und 2, wobei die Elektrodenanordnung des Sensorsystems (22) Elektroden (38) umfasst, die so angeordnet sind, dass sie die Muster auch stromabwärts der Strömung erfassen.

4. System (20) nach einem der Ansprüche 1 bis 3, wobei das permselektive Medium (11) des Sensorsystems (22) mindestens ein Medium umfasst, das ausgewählt ist aus der Gruppe bestehend aus: einer Nanostruktur und einer nanoporösen Membran.

5. System (20) nach einem der Ansprüche 1 bis 4, wobei das permselektive Material des Sensorsystems (22) ein Kationenaustauschermaterial oder ein Anionenaustauschermaterial umfasst.

6. System (20) nach einem der Ansprüche 1 bis 5, wobei das permselektive Material des Sensorsystems (22) polymer ist.

7. System (20) nach einem der Ansprüche 1 bis 6, wobei der mindestens eine Strömungsparameter aus der Gruppe bestehend aus Strömungsgeschwindigkeit und Strömungsrichtung ausgewählt ist.

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8. System (20) nach einem der Ansprüche 1 bis 7, wobei der Signalprozessor (30) so konfiguriert ist, dass er mindestens einen Strömungsparameters durch Extrahieren mindestens eines elektrischen Parameters aus den Erfassungssignalen und Korrelieren des mindestens einen elektrischen Parameters mit dem mindestens einen Strömungsparameter bestimmt.

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9. System (20) nach einem der Ansprüche 1 bis 8, wobei der Signalprozessor (30) so konfiguriert ist, dass er eine Zeit bestimmt, die erforderlich ist, damit die Erfassungssignale Sättigung zeigen, und die Zeit mit dem mindestens einen Strömungsparameter korreliert.

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10. System (20) nach einem der Ansprüche 1 bis 9, wobei der mindestens eine Mikrokanal (12) ein verzweigter fluidischer Mikrokanal ist, und wobei das permselektive Medium (11) eine Verbindung zwischen zwei Zweigen des verzweigten Mikrokanals herstellt.

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11. System (20) nach einem der Ansprüche 1 bis 9, wobei das Sensorsystem (22) zwei sekundäre Mikrokanäle (33, 35) umfasst, die im Allgemeinen parallel zum Mikrokanal (12) positioniert sind, sodass das permselektive Medium (11) jeden der sekundären Mikrokanäle (33, 35) mit dem Mikrokanal (12) verbindet, und wobei die Elektroden (28) so angeordnet sind, dass sie das elektrische Feld entlang der sekundären Mikrokanäle (33, 35) erzeugen.

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12. System (20) nach einem der Ansprüche 1 bis 11, wobei das mikrofluidische System (20) eine Pumpe (42) zum Erzeugen der Strömung und eine Steuerung (37) umfasst, die so konfiguriert ist, dass die Pumpe (42) in Reaktion auf den bestimmten Strömungsparameter gesteuert wird.

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13. Verfahren zur Erfassung eines Fluidstroms in einem Mikrokanal (12), wobei das Verfahren umfasst:

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Verbinden einer Vielzahl von Elektroden mit einer Energiequelle, um ein elektrisches Feld über ein permselektives Medium (11) zu erzeugen, das im Mikrokanal (12) in Kontakt mit dem Fluid positioniert ist, wodurch mittels des Konzentrationspolarisationseffekts angereicherte und verarmte Ionenkonzentrationen im Mikrokanal (12) in der Nähe gegenüberliegender Enden (24, 26) des permselektiven Mediums (11) gebildet werden;

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Erfassen von Signalen, die Muster der Ionenkonzentration anzeigen, die durch den Fluidstrom im Mikrokanal (12) bewirkt werden; und Analysieren der Erfassungssignale, um mindestens einen Strömungsparameter zu bestimmen, der den Strom charakterisiert;

dadurch gekennzeichnet, dass das Erfassen durch ein Elektrodenpaar (28) erfolgt, das auch zur Erzeugung des elektrischen Feldes verwendet wird;

wobei der mindestens eine Strömungsparameter aus der Gruppe bestehend aus einer Strömungsgeschwindigkeit, einer Änderung der Strömungsgeschwindigkeit, einer Strömungsrichtung, einem Geschwindigkeitsvektorfeld, einer Änderung des Geschwindigkeitsfelds und einer Richtung des Geschwindigkeitsfeldvektors ausgewählt wird.

14. Verfahren nach Anspruch 13, wobei das Erzeugen des elektrischen Felds für eine Dauer fortgesetzt wird, die länger ist als eine Zeit, die erforderlich ist, damit die Erfassungssignale Sättigung zeigen.

15. Verfahren nach einem der Ansprüche 13 und 14, wobei das Fluid ein Lösungsmittel und gelöste Spezies umfasst, und wobei die Elektroden eine Reaktion mit nur einem des Lösungsmittels und der gelösten Spezies unterstützen.

Revendications

1. Système microfluidique (20) comprenant :

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un microcanal (12) ; et
un système de capteur (22) permettant de détecter l'écoulement de fluide dans ledit microcanal (12), le système de capteur (22) comprenant :

un milieu permselectif (11) positionné pour entrer en contact avec le fluide dans le microcanal (12) ;

une source d'alimentation (36) ;

un agencement d'électrodes (28), pouvant être connectées à ladite source d'alimentation (36) et conçues pour générer un champ électrique à travers ledit milieu permselectif (11) formant ainsi, par l'effet de polarisation de concentration, des concentrations ioniques enrichies et ioniques appauvries dans ledit microcanal (12) près des extrémités opposées respectives (24, 26) dudit milieu permselectif (11), et pour générer des signaux de détection indiquant les motifs de ladite concentration d'ions qui sont effectués par l'écoulement de fluide dans ledit

microcanal (12) ; et
un processeur de signal (30) permettant
d'analyser lesdits signaux de détection pour
déterminer au moins un paramètre d'écou-
lement caractérisant ledit écoulement ;

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caractérisé en ce que :

au moins une paire d'électrodes (28) qui gé-
nèrent ledit champ électrique génèrent éga-
lement lesdits signaux de détection ;
dans lequel ledit au moins un paramètre
d'écoulement est sélectionné dans le grou-
pe constitué par un débit, un changement
de débit, une direction d'écoulement, un
champ de vecteur de vitesse, un change-
ment du champ de vitesse et une direction
du vecteur de champ de vitesse.

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2. Système (20) selon la revendication 1, dans lequel
ledit agencement d'électrodes (28) dudit système de
capteur (22) est conçu pour détecter lesdits motifs
sur un ou deux côtés opposés de l'au moins une
desdites extrémités (24, 26) dudit milieu permsélectif
(11).

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3. Système (20) selon l'une quelconque des revendi-
cations 1 et 2, dans lequel ledit agencement d'élec-
trodes dudit système de capteur (22) comprend des
électrodes (38) conçues pour détecter lesdits motifs
également en aval dudit écoulement.

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4. Système (20) selon l'une quelconque des revendi-
cations 1 à 3, dans lequel ledit milieu permsélectif
(11) dudit système de capteur (22) comprend au
moins un milieu sélectionné dans le groupe constitué
par : une nanostructure et une membrane nanopor-
euse.

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5. Système (20) selon l'une quelconque des revendi-
cations 1 à 4, dans lequel ledit matériau permsélectif
dudit système de capteur (22) comprend un matériau
échangeur de cations ou un matériau échangeur
d'anions.

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6. Système (20) selon l'une quelconque des revendi-
cations 1 à 5, dans lequel ledit matériau permsélectif
dudit système de capteur (22) est polymérique.

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7. Système (20) selon l'une quelconque des revendi-
cations 1 à 6, dans lequel ledit au moins un paramè-
tre d'écoulement est sélectionné dans le groupe
constitué par le débit et la direction d'écoulement.

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8. Système (20) selon l'une quelconque des revendi-
cations 1 à 7, dans lequel ledit processeur de signal
(30) est configuré pour déterminer ledit au moins un
paramètre d'écoulement par extraction desdits si-

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gnaux de détection d'au moins un paramètre élec-
trique, et par corrélation dudit au moins un paramètre
électrique audit au moins un paramètre d'écoule-
ment.

9. Système (20) selon l'une quelconque des revendi-
cations 1 à 8, dans lequel ledit processeur de signal
(30) est configuré pour déterminer un temps requis
pour que lesdits signaux de détection présentent une
saturation, et pour corréler ledit temps audit au moins
un paramètre d'écoulement.

10. Système (20) selon l'une quelconque des revendi-
cations 1 à 9, dans lequel ledit au moins un micro-
canal (12) est un microcanal fluide ramifié, et
dans lequel ledit milieu permsélectif (11) se relie en-
tre deux branches dudit microcanal ramifié.

11. Système (20) selon l'une quelconque des revendi-
cations 1 à 9, dans lequel ledit système de capteur
(22) comprend deux microcanaux secondaires (33,
35) positionnés généralement parallèlement audit
microcanal (12) de sorte que ledit milieu permsélectif
(11) relie chacun desdits microcanaux secondaires
(33, 35) audit microcanal (12), et dans lequel lesdites
électrodes (28) sont conçues pour générer ledit
champ électrique le long desdits microcanaux se-
condaires (33, 35).

12. Système (20) selon l'une quelconque des revendi-
cations 1 à 11, dans lequel le système microfluidique
(20) comprend une pompe (42) permettant de gé-
nérer ledit écoulement, et un dispositif de commande
(37) conçu pour commander ladite pompe (42) en
réponse audit paramètre d'écoulement.

13. Procédé de détection d'écoulement de fluide dans
un microcanal (12), le procédé consistant à :

connecter une pluralité d'électrodes à une sour-
ce d'alimentation pour générer un champ élec-
trique à travers un milieu permsélectif (11) po-
sitionné dans le microcanal (12), en contact
avec le fluide, formant ainsi, par l'effet de pola-
risation de concentration, des concentrations io-
niques enrichies et ioniques appauvries dans le-
dit microcanal (12) près des extrémités oppo-
sées (24, 26) dudit milieu permsélectif (11) ;
détecter des signaux indiquant des motifs de la-
dite concentration d'ions, lesquels sont effec-
tués par l'écoulement de fluide dans ledit micro-
canal (12) ; et
analyser lesdits signaux de détection pour dé-
terminer au moins un paramètre d'écoulement
caractérisant ledit écoulement ;
caractérisé en ce que ladite détection est ef-
fectuée par une paire d'électrodes (28) qui sont
également utilisées pour ladite génération dudit

champ électrique ;
dans lequel ledit au moins un paramètre d'écoulement est sélectionné dans le groupe constitué par un débit, un changement de débit, une direction d'écoulement, un champ de vecteur de vitesse, un changement du champ de vitesse et une direction du vecteur de champ de vitesse.

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14. Procédé selon la revendication 13, dans lequel ladite génération dudit champ électrique est poursuivie pendant une durée supérieure à un temps nécessaire pour que lesdits signaux de détection présentent une saturation.

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15. Procédé selon l'une quelconque des revendications 13 et 14, dans lequel le fluide comprend un solvant et des espèces dissoutes, et dans lequel lesdites électrodes supportent la réaction avec un seul élément parmi ledit solvant et lesdites espèces dissoutes.

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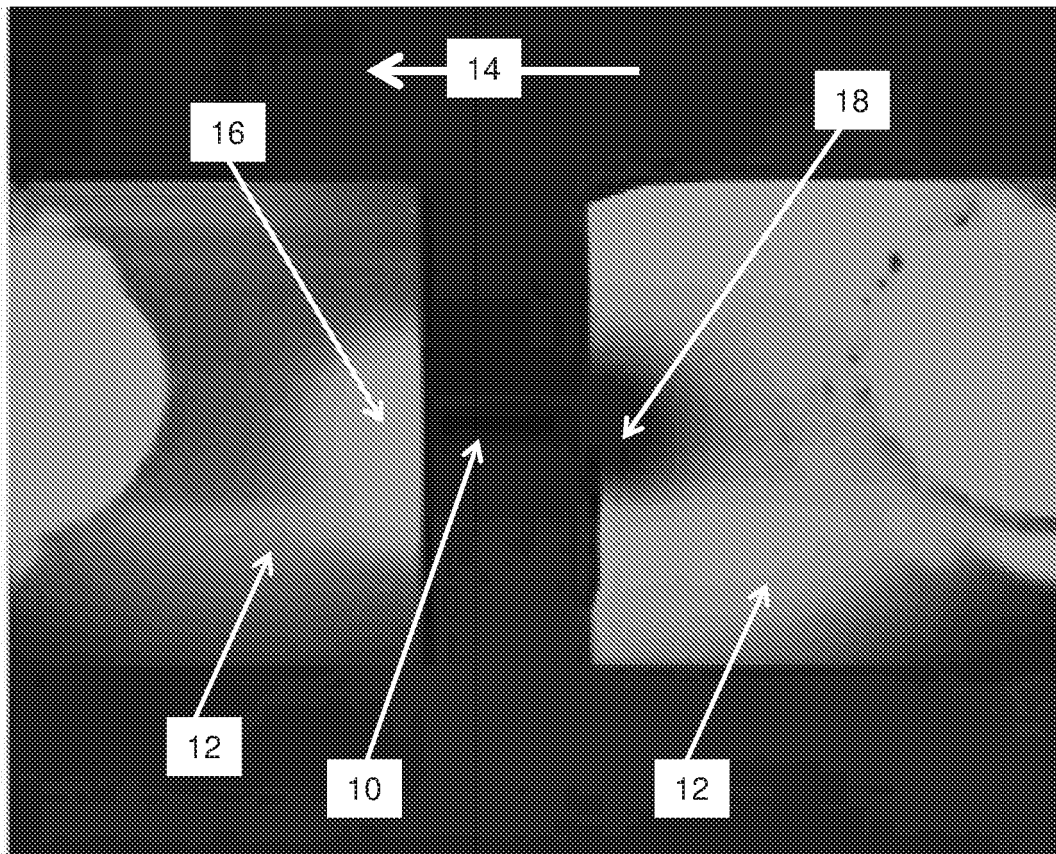


FIG. 1A

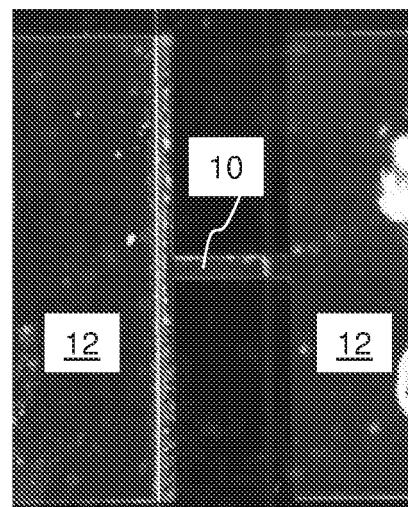


FIG. 1B

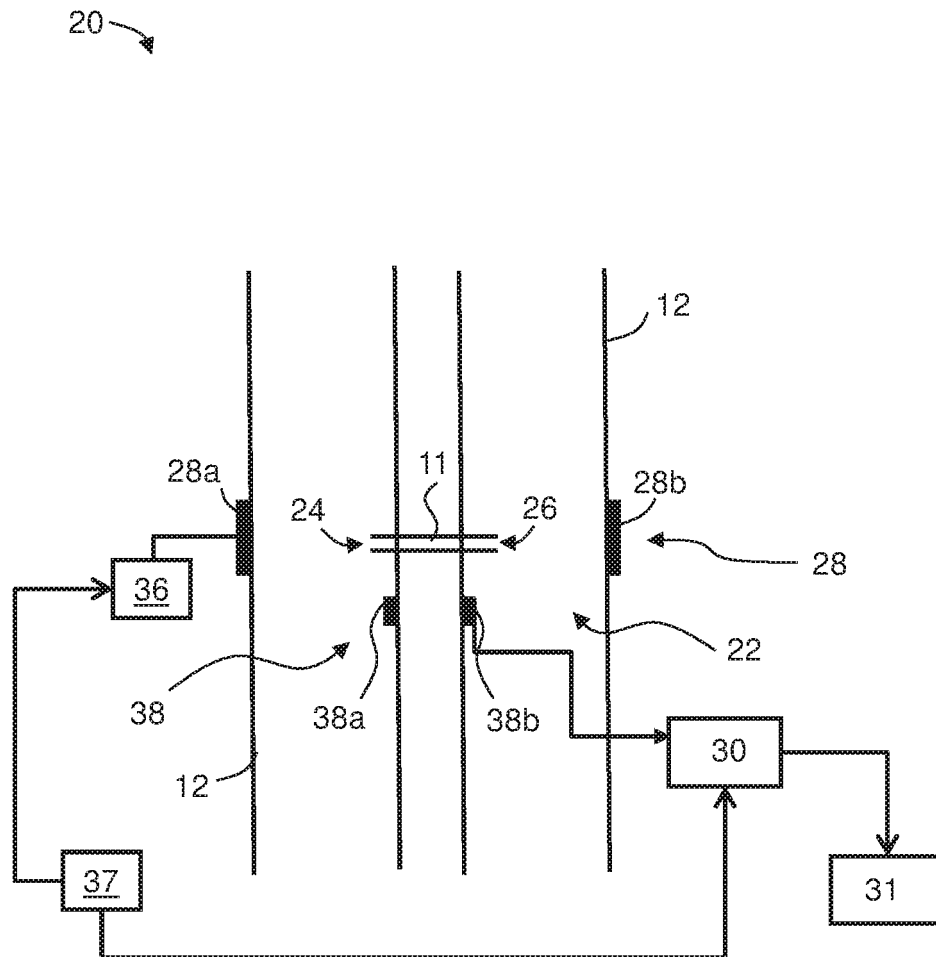


FIG. 2

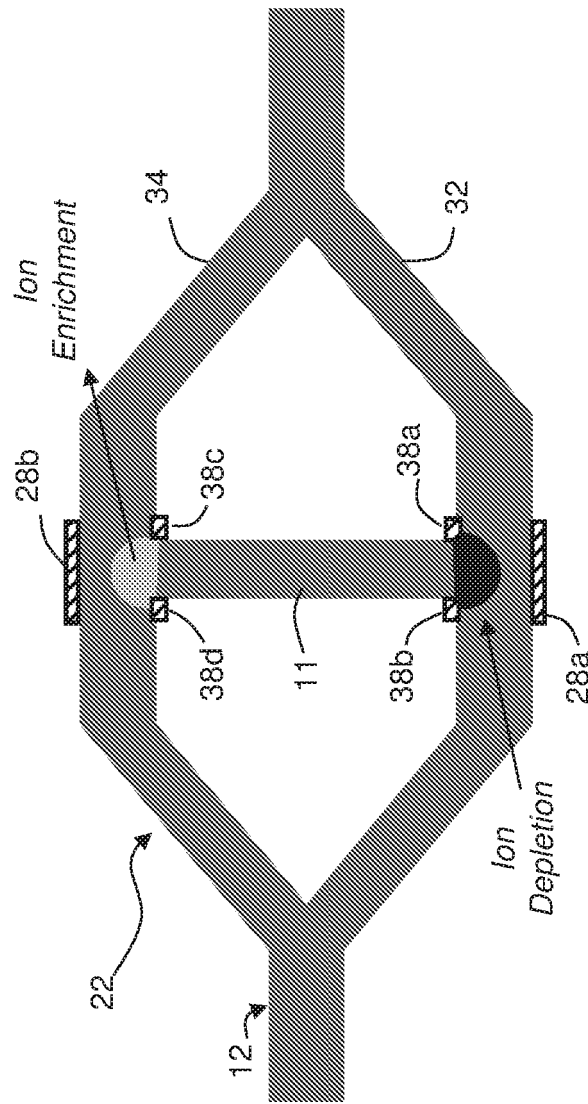


FIG. 3A

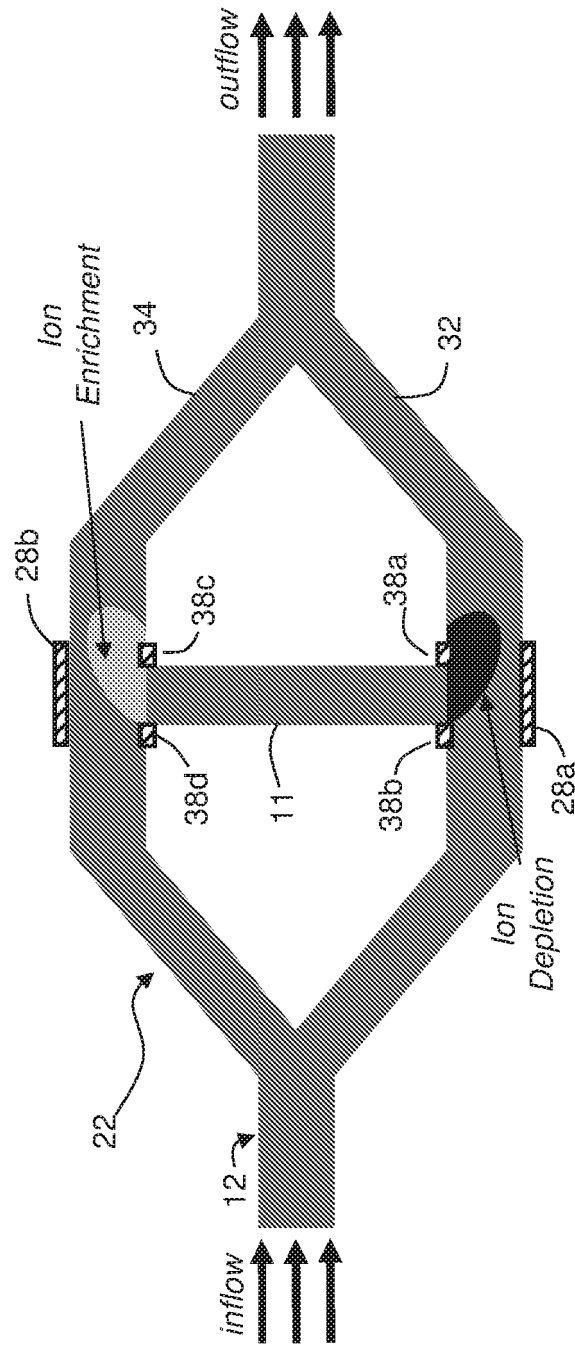


FIG. 3B

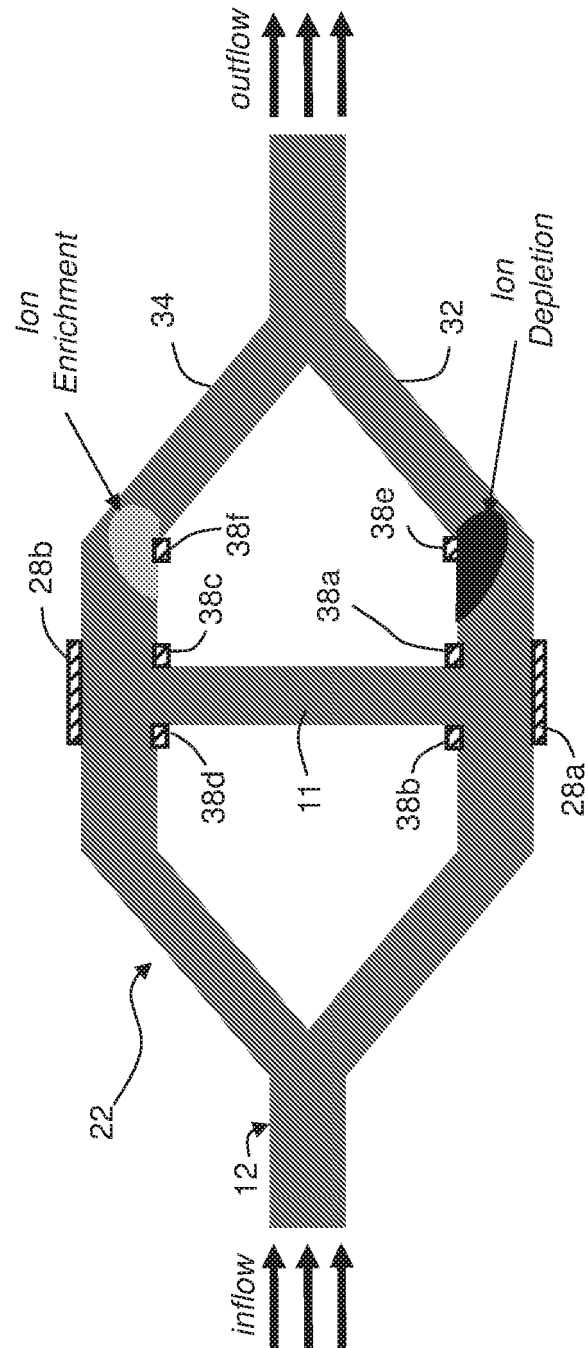
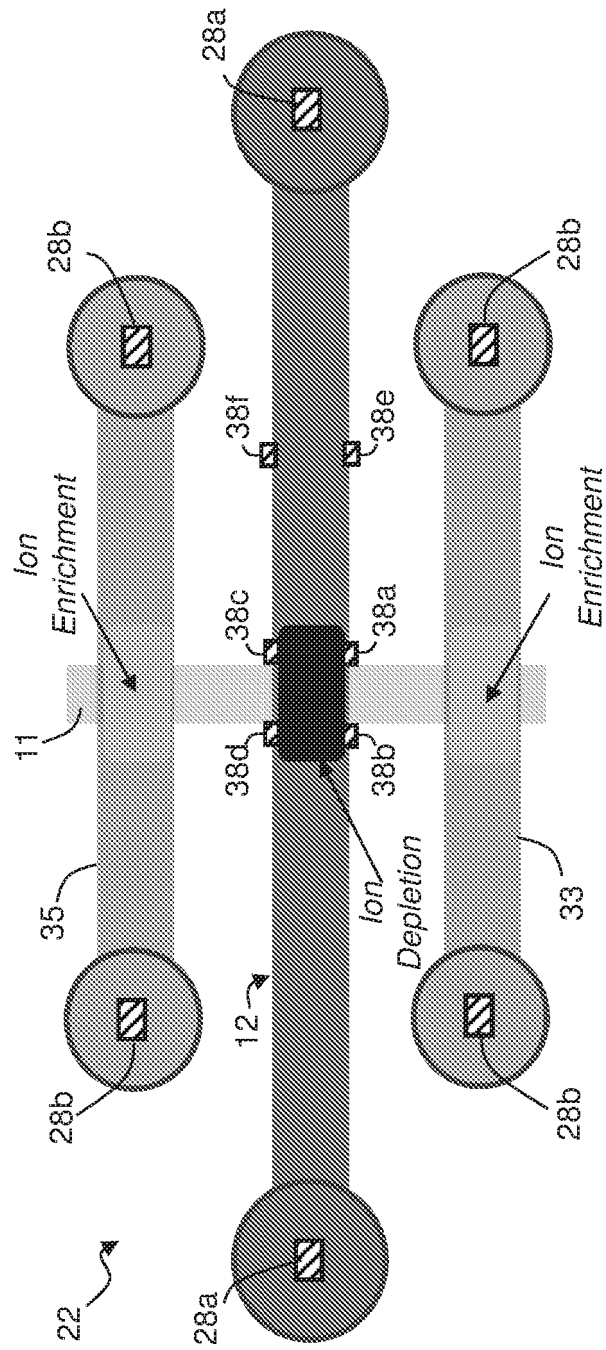


FIG. 3C



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G
L

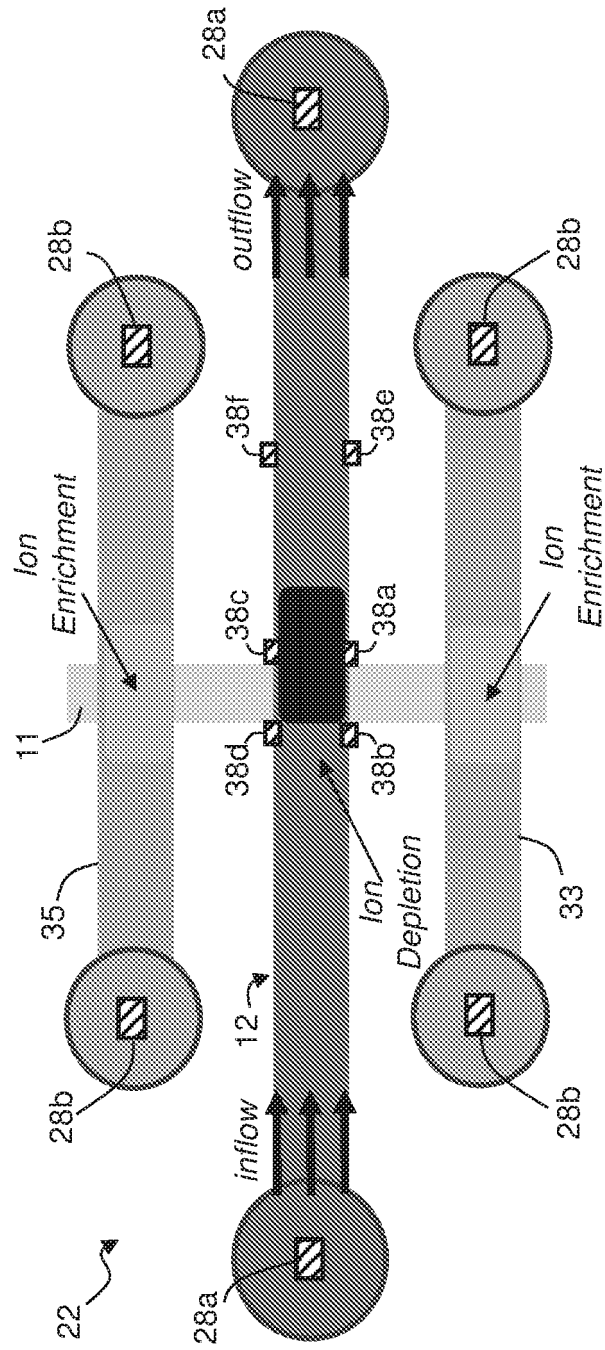


FIG. 4B

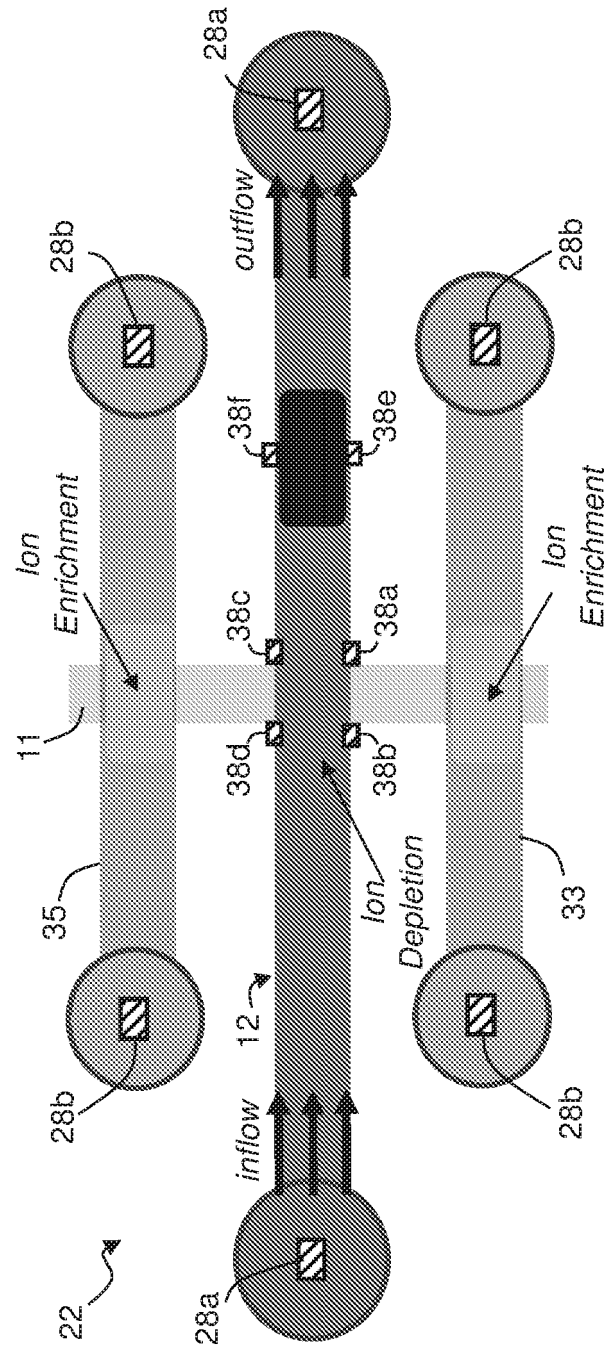


FIG. 4C

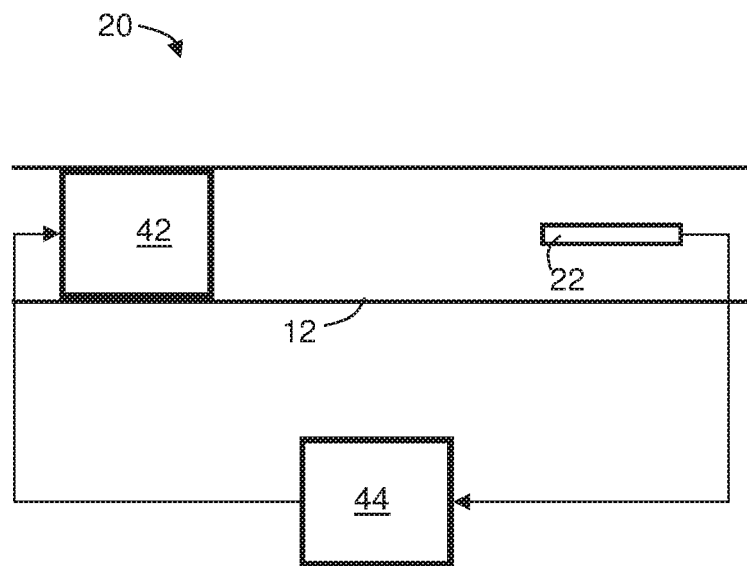


FIG. 5

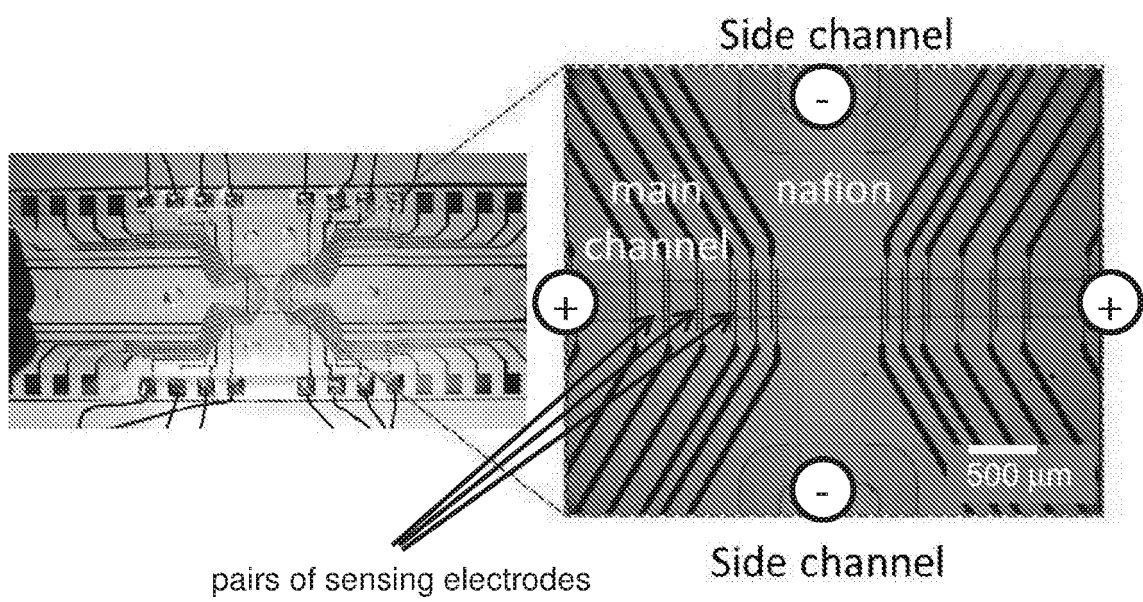


FIG. 6A

FIG. 6B

FIG. 7A

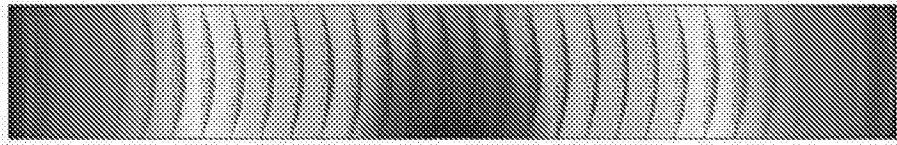


FIG. 7B

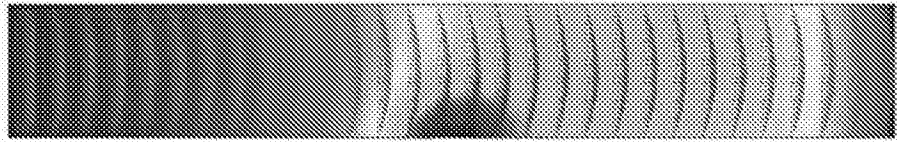


FIG. 7C

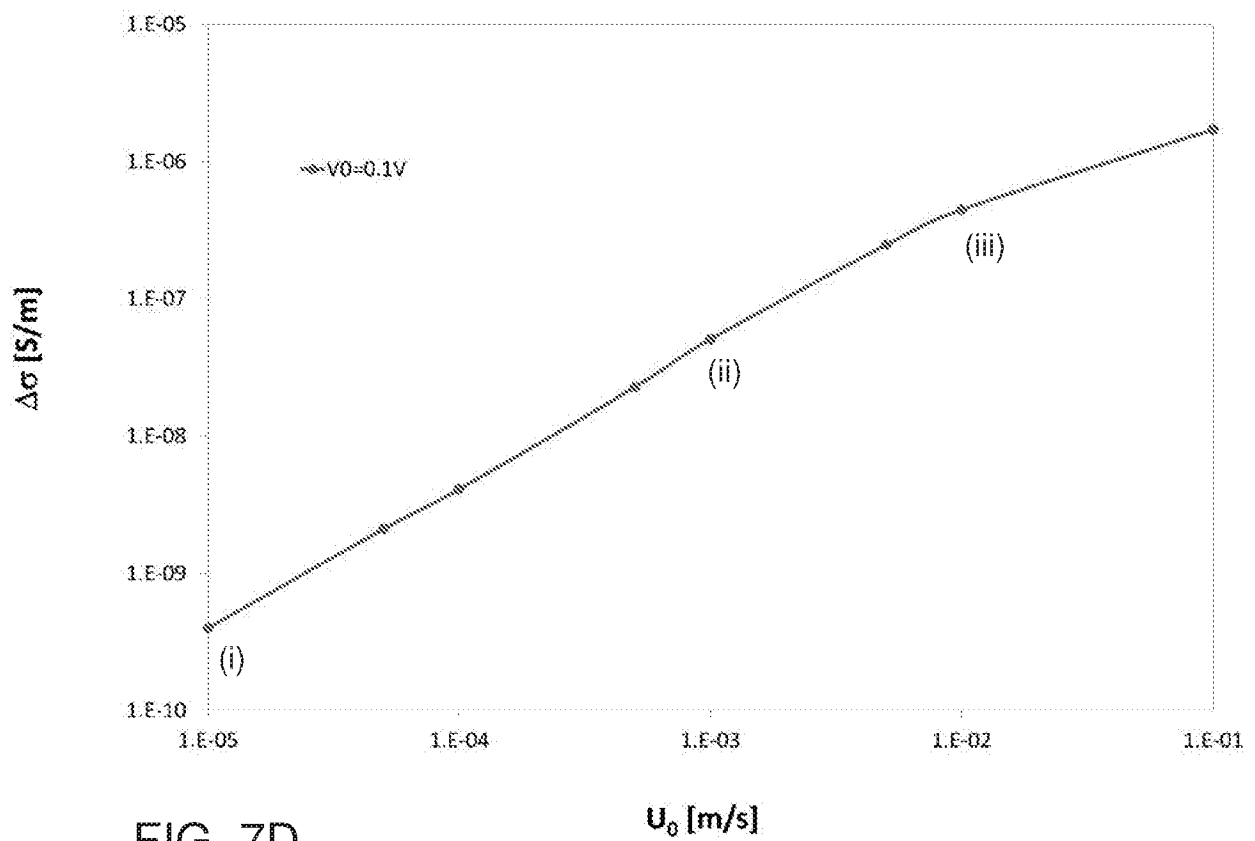
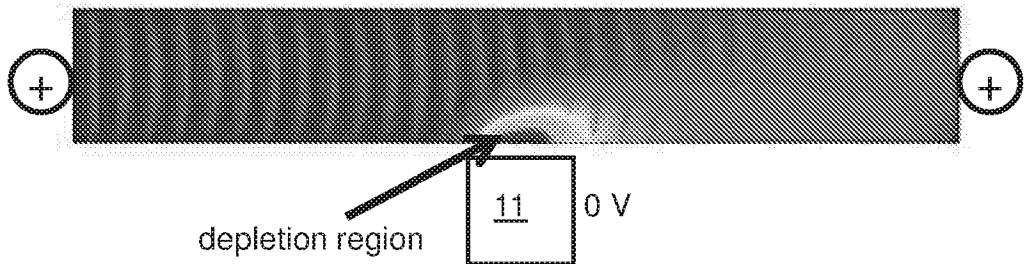


FIG. 7D

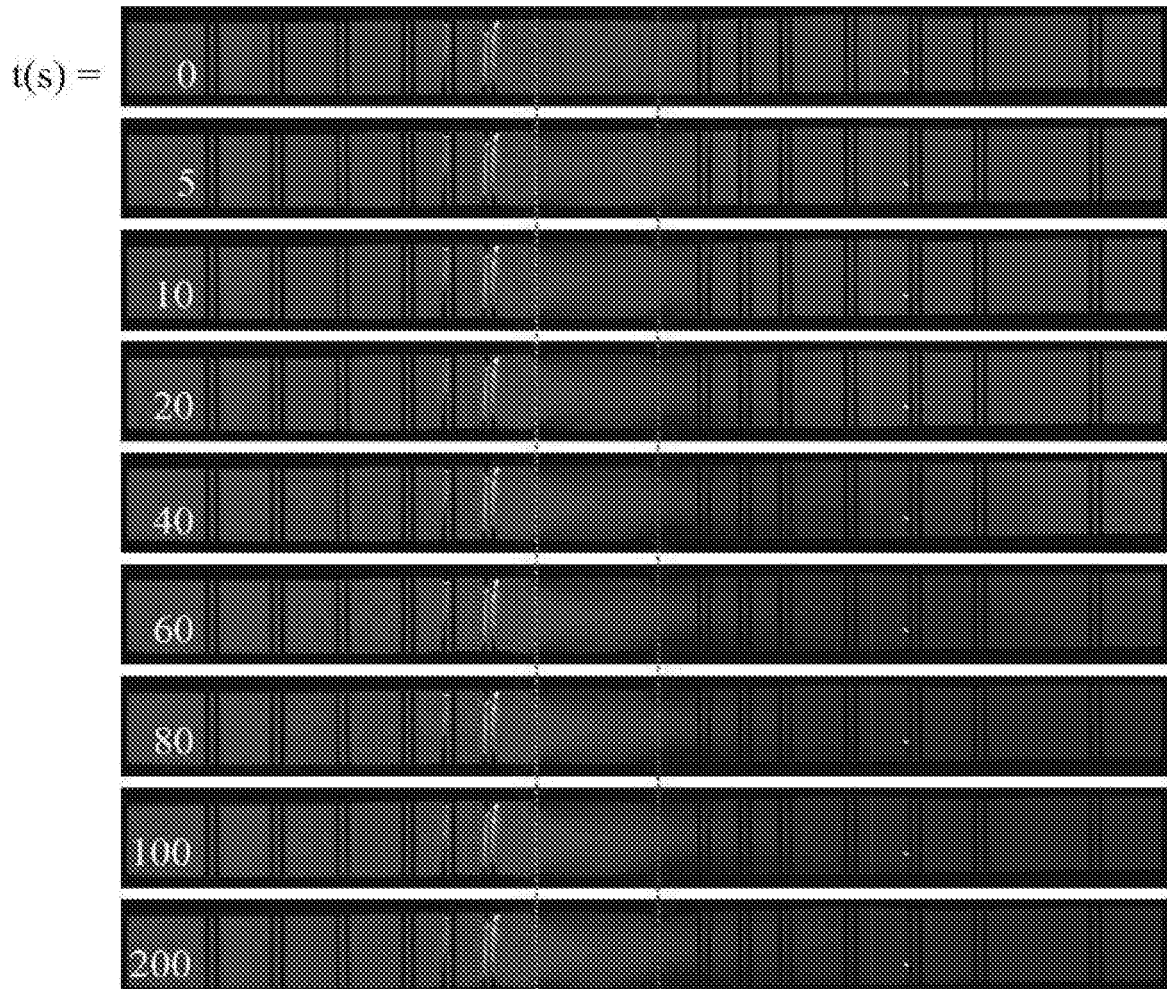


FIG. 8A

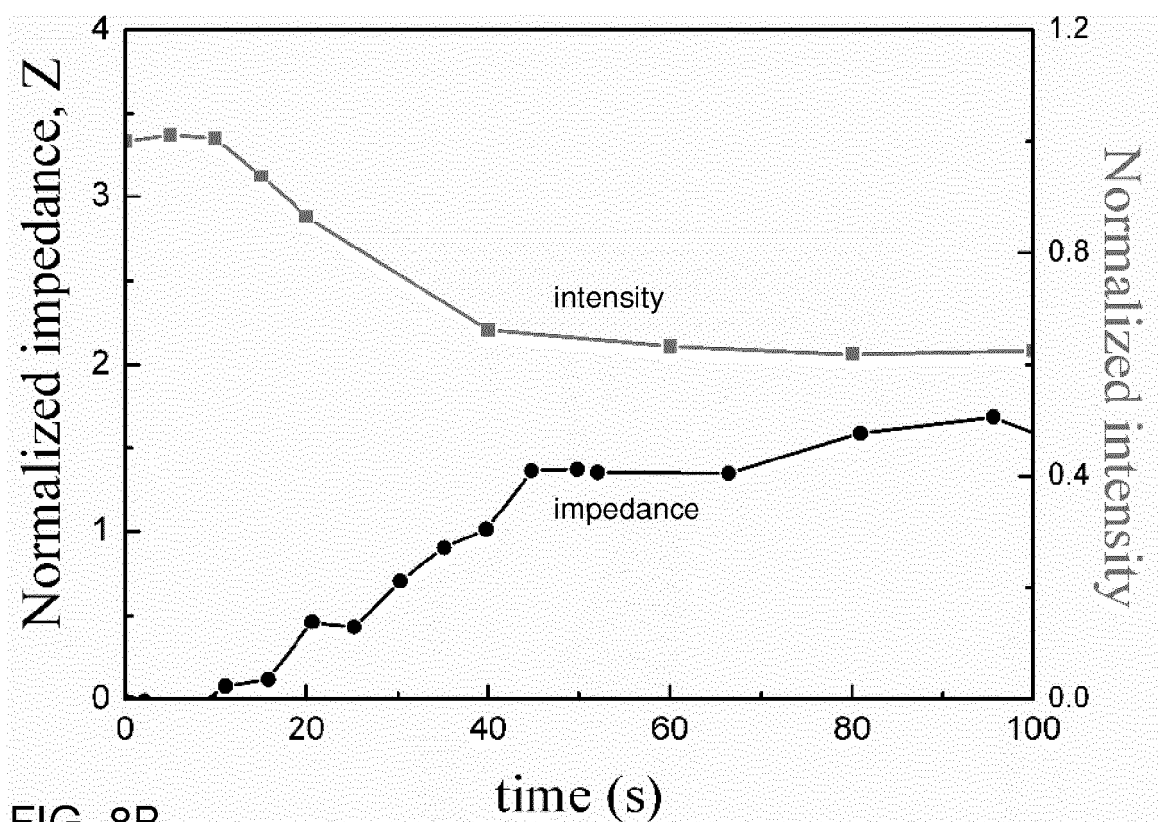


FIG. 8B

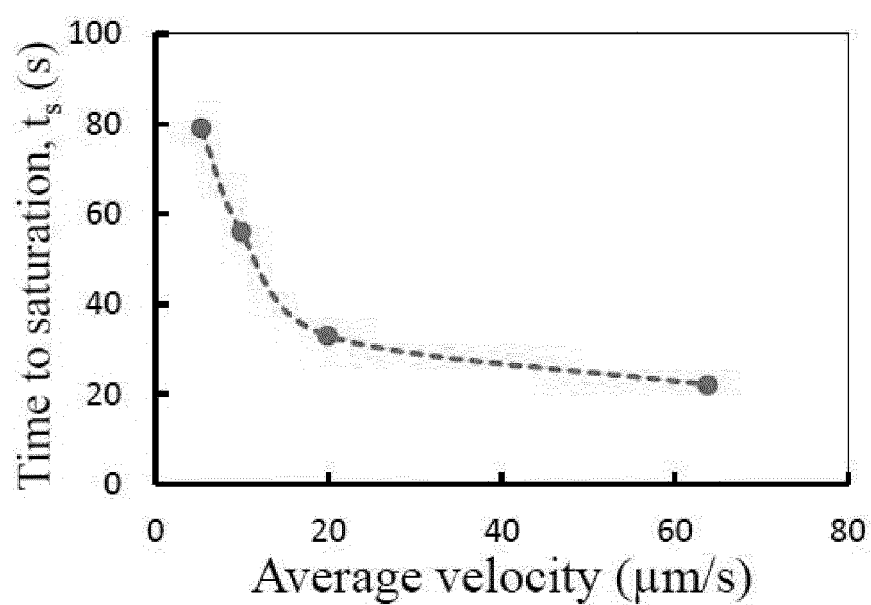


FIG. 9A

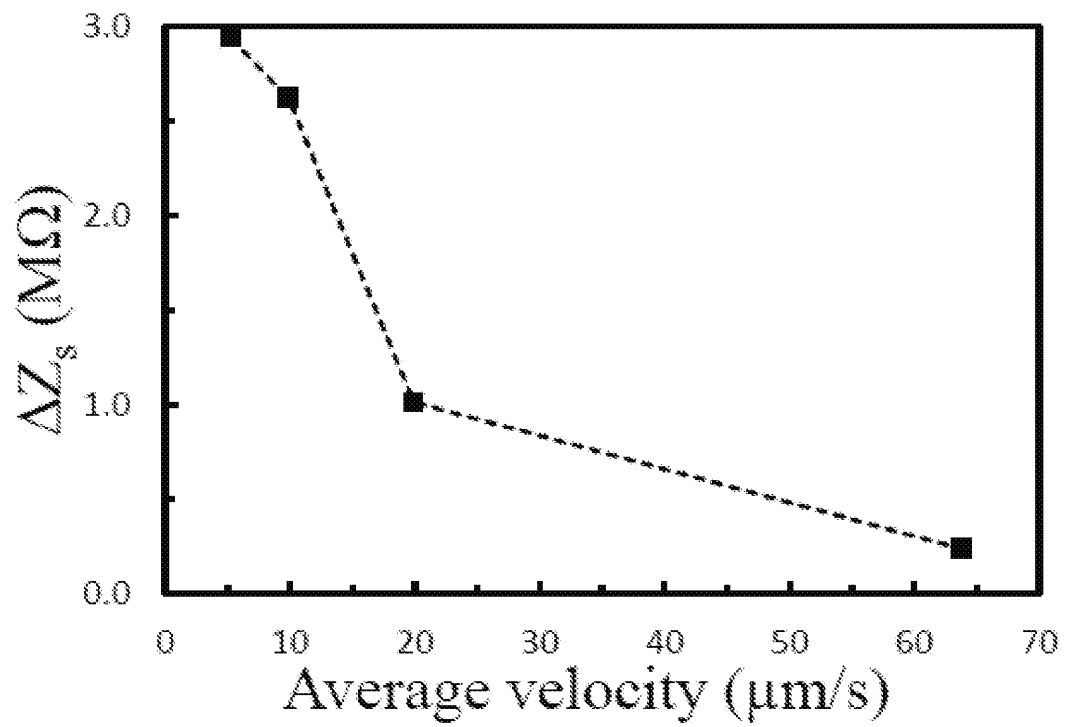


FIG. 9B

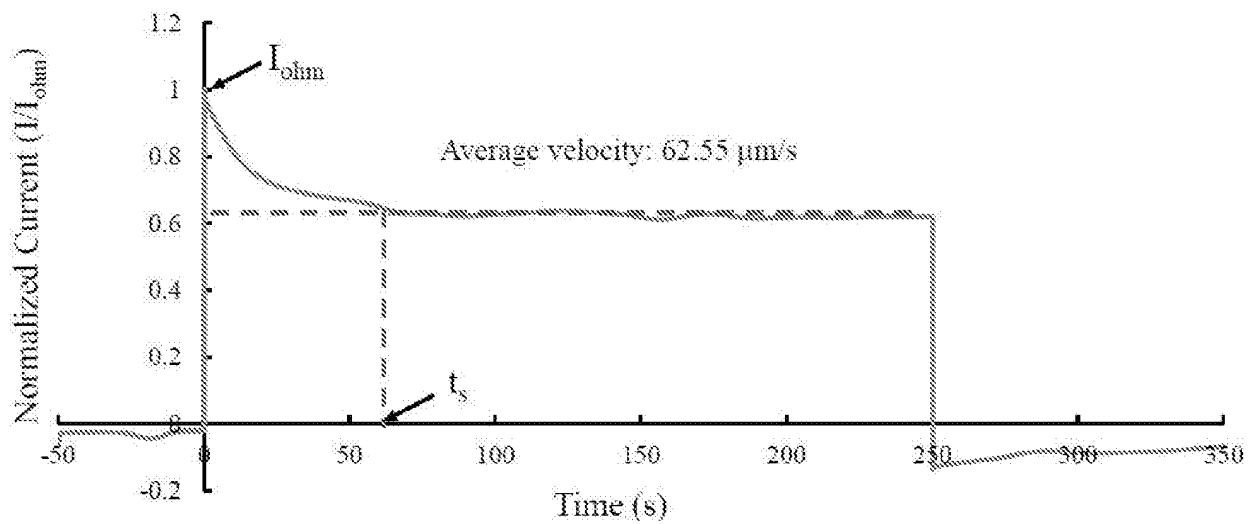


FIG. 10A

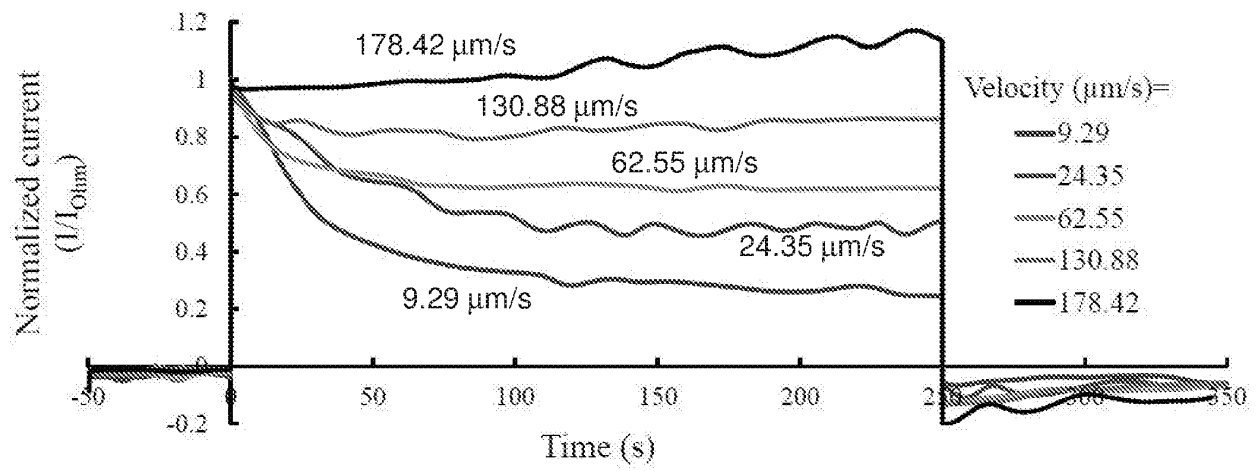


FIG. 10B

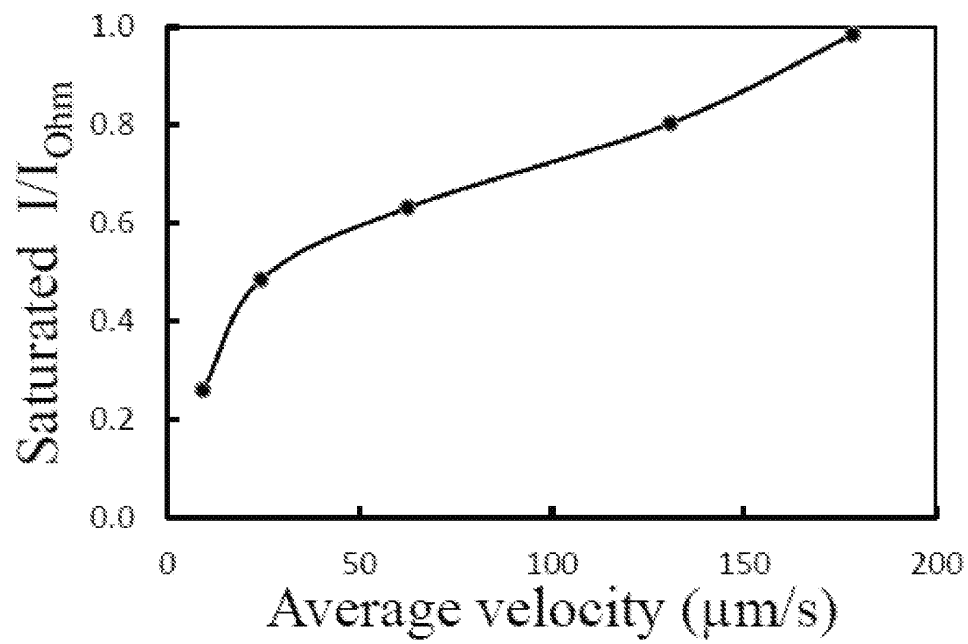


FIG. 10C

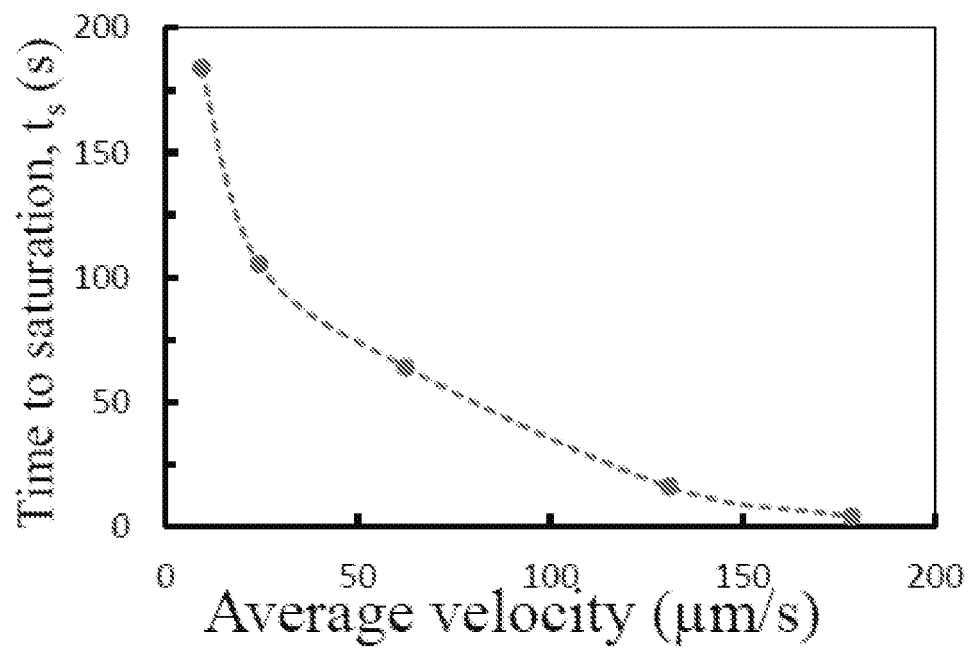


FIG. 10D

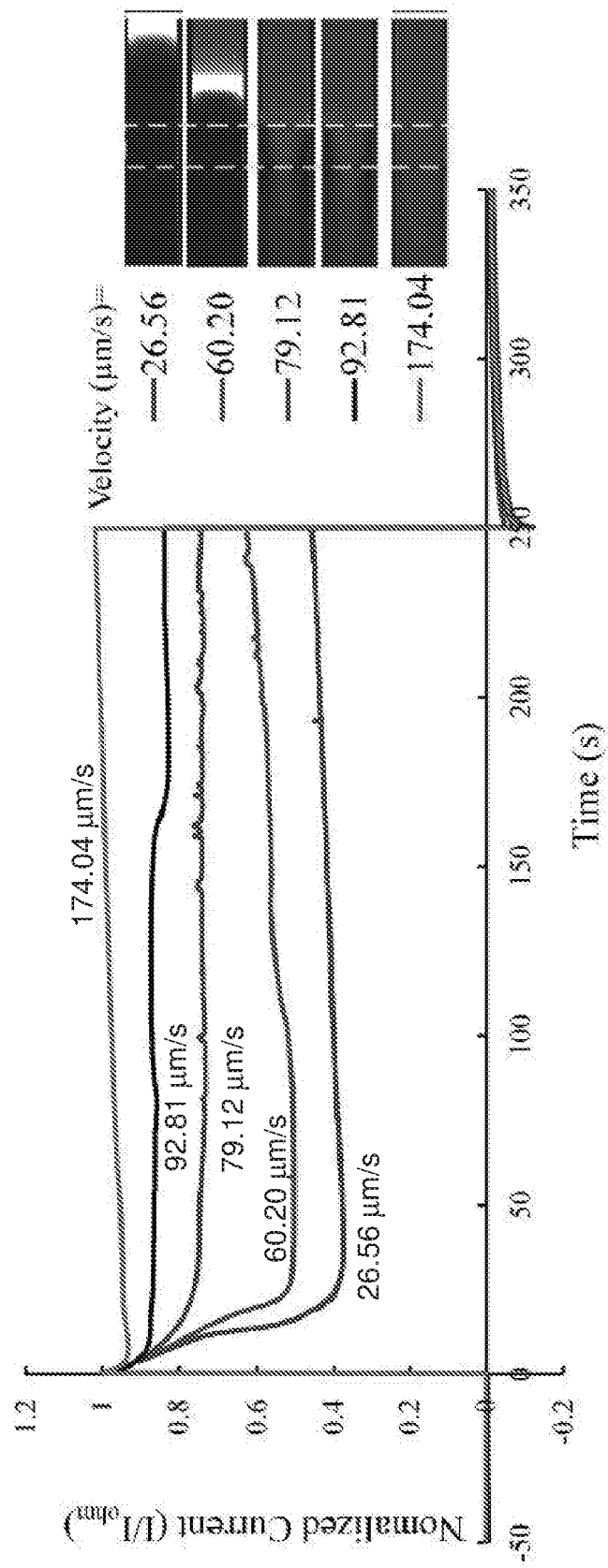


FIG. 11A

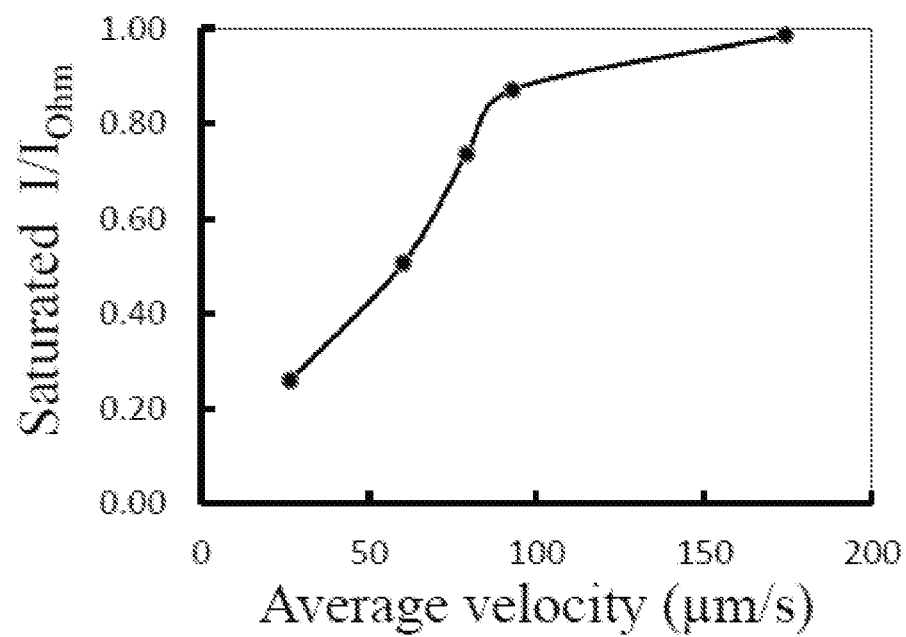


FIG. 11B

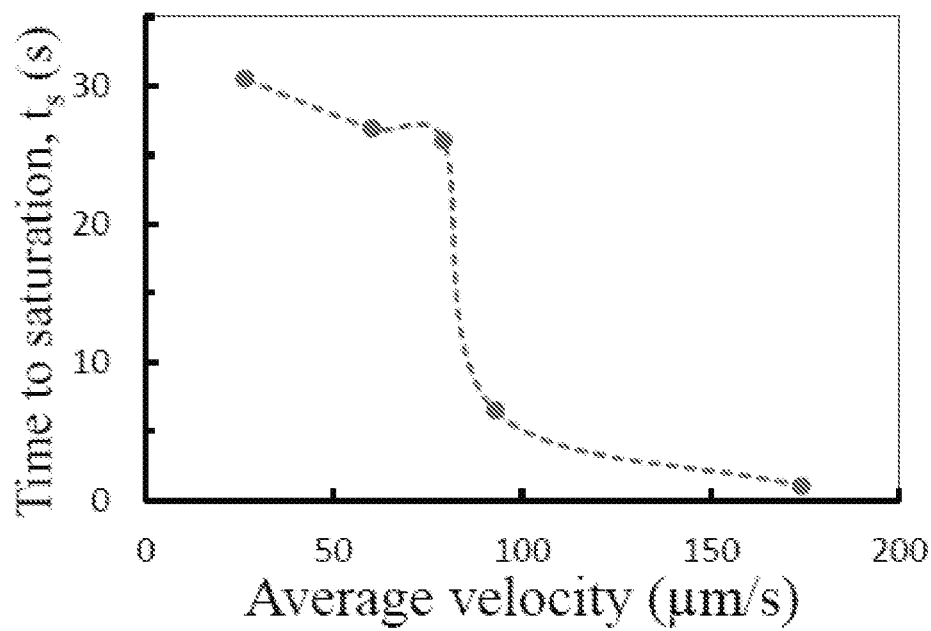


FIG. 11C

REFERENCES CITED IN THE DESCRIPTION

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